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Proceedings: Forest Vegetation Simulator Conference
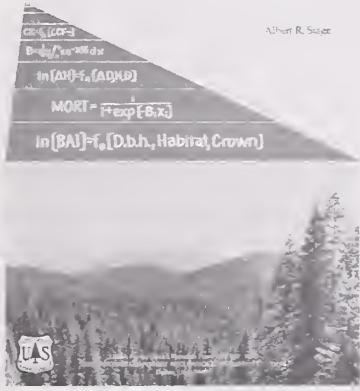
PROGNOSIS MODEL FOR
STAND DEVELOPMENT
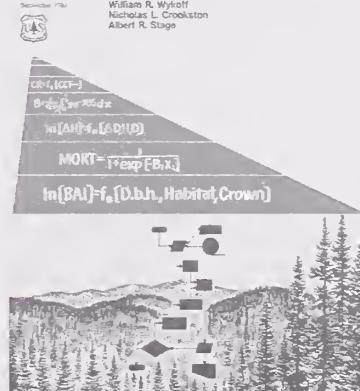
User's Guide to the
Stand Prognosis
Model

COVER: A User's
Guide to the
CANOPY and
SHRUBS Extension
of the Stand
Prognosis Model

User's Guide to the
Parallel Processing
Extension of the
Prognosis Model

User's Manual for Western
Root Disease Model

User's Guide to the
Event Monitor Part
of Prognosis Model
Version 6

User's Guide to Version 2
of the Regeneration
Establishment Model:
Part of the Prognosis Model

User's Guide to the Western
Spruce Budworm Modeling
System

Predicting Regeneration
Establishment With the
Prognosis Model

The Compilers

Richard Teck is a Forester/Operations Research Analyst with the U.S. Forest Service's Forest Management Service Center in Fort Collins, CO. He oversees the National FVS Training Program and the National FVS User-Support/Hotline Program. He is responsible for maintaining the software that links FVS to the Forest Service's Regional vegetation data bases. He is the primary contact at the Service Center for forest planning teams. He has been with the Center since 1991. Before that he was with the Northeastern Forest and Range Experiment Station working on the NE-TWIGS individual-tree modeling project in Delaware, OH.

Melinda Moeur is a Research Forester with the Rocky Mountain Research Station's Research Work Unit on Quantitative Analysis of Forest Resources Responses, in Moscow, ID. The unit's long-term mission is to develop models of forest vegetation at the tree, stand, ecosystem, and global levels, and to develop procedures for using the models in natural resource inventory, monitoring, and planning systems. Dr. Moeur's research contributions have included models of forest canopy and understory vegetation development and structure. These models have been incorporated into the COVER extension of FVS.

Judy Adams joined the Forest Health Technology Enterprise Team in 1991. The Team is a part of Forest Health Protection and is in Fort Collins, CO. This staff has been instrumental in the development and support of insect and pathogen models since the early 1980's. These models link directly into FVS, requiring continual modifications and upgrading as a result of changes made to FVS or the insect and pathogen models. Judy's current projects include the on-going maintenance of these models, coordinating training sessions, and providing user support. She has also increased the accessibility of the models, documents, and other related information by developing and supporting a bulletin board system and providing availability through the internet.

Research Summary

The Forest Vegetation Simulator (FVS) is an analytical tool used in the United States, Canada, and other countries to aid natural resource managers in projecting the development of forest stands under varying land management options. First appearing two decades ago under the name "Prognosis," FVS is a suite of computer programs developed by researchers who, working with FVS users, continually refine the program to meet changing natural resource needs and to incorporate new technology. The resulting, ever-evolving tool is used increasingly in strategic planning for ecosystem management of public and private lands and for analysis at project, watershed, and regional levels. This proceedings came out of the first FVS conference, held in 1997 at Fort Collins, CO, and includes 33 papers dealing with habitat modeling, landscape analysis, forest planning, forest health assessment, ecological processes, modeling vegetation dynamics, and new technologies. Researchers detail "how to" guidelines. Public and private land managers detail how they used FVS in forest planning and management at such sites as the Custer State Park, the White River National Forest, the Sierra Nevada ecosystem, the Columbia River Basin, industrial forest lands, and the Menominee Indian Reservation. Authors cover issues as diverse as forest inventory, insect and disease model applications, spotted owl policy issues, modeling riparian systems, and integrating computer visualization as an analytic tool. Future enhancements and innovative applications of FVS will continue to depend upon close working relations between the developers and the FVS user community.

Proceedings: Forest Vegetation Simulator Conference

Fort Collins, CO, February 3–7, 1997

Compilers:

Richard Teck
Melinda Moeur
Judy Adams

Preface

The Forest Vegetation Simulator (FVS) Conference was held at the USDA, Forest Service's Forest Management Service Center (FSMC), Fort Collins, CO, February 3-7, 1997. Papers presented at this conference form the contents of this proceedings and are arranged by conference topic.

The conference brought together resource professionals interested in forest growth simulation to foster a long overdue interchange between and among FVS developers and the FVS model user community. In addition to highlighting FVS as an analytical tool, the conference provided a venue for observing how the model has been used by other staffs, organizations, and agencies.

The conference organizers hoped to accomplish three primary objectives. First was to document how forest vegetation simulation is being incorporated into project-level analysis, watershed analysis, and strategic planning. This provided a forum to learn approaches and methodologies used and as such, presenters were encouraged to highlight the strengths and weaknesses of FVS with respect to those analyses. The second conference objective was to foster the sharing of ideas and analytical techniques by bringing representatives of the FVS user community together in one place. The third objective was to identify future FVS development needs and address opportunities to integrate with other analytical tools currently in use. We feel the conference successfully met its intended objectives.

But what about you, the reader? Many of you may be reviewing these proceedings without any strong connection to FVS. What could we say to convince you to read through some of the excellent papers that appear here? Well, perhaps you did not know that FVS is the most widely used forest growth model in the United States. Since the early 1990's, more than 1,000 individuals have received formal FVS use training. Or perhaps you were unaware that the U.S. Forest Service has been using FVS continuously for more than 20 years. You may be surprised to know that the FVS user community includes, among others, industrial forest products corporations, private forestry consulting firms, Federal and State land management agencies, a Canadian province, and many universities.

But how is it applied? Good question! We hope the papers in this proceedings will demonstrate the range of this analysis tool. For starters, FVS has been used extensively for developing forest product yield tables for forest planning. If you are interested in strategic planning, you might wish to read about the Black Hills National Forest planning effort (Wisler and Rupe), the Custer State Park resource management plan (Hill), or the Menominee Reservation forest plan (Wilson, D.)

If you are interested in large-scale regional assessments, you may want to read about the California spotted owl analysis (Wilson, L.), the Columbia River Basin assessment (Stage), or the Sierra Nevada ecosystem project (Cousar). Interested in mid-scale assessments such as at the watershed level? You might find the Deadwood ecosystem analysis (Steele) worthwhile.

For many resource professionals, forest health is an increasing concern. The Boise National Forest (Roberts and Weatherby) and the White River National Forest (Eager and Angwin) have developed some interesting analysis techniques for evaluating forest health. With the catastrophic fire seasons of the 1980's and 1990's, a renewed interest in fuels management and the role of fire in forest health has led to the development of a fire effects model extension to FVS (Buekema and others).

In addition to forest health, biological diversity is a hot natural resource issue of the 1990's. For many of us, simply defining diversity is difficult. But without some standardized procedure to identify diversity, it is difficult to determine whether our management practices are increasing, decreasing, or simply stabilizing the diversity that currently exists. Boise Cascade Corporation has begun to address this issue of diversity and its impact on its management decisions by developing an Ecosystem Diversity Matrix Projection System (Scharosch and others) for lands in the Idaho Southern Batholith landscape in west-central Idaho.

Good data are relevant to all scales of analysis—and not only good data, but how they are collected and transformed into useful information. The U.S. Forest Service's Pacific Northwest Region is designing integrated resource inventories along with sophisticated inventory processing software to do just that (Gregg and Goheen). Likewise, the Bureau of Indian Affairs oversees a continuous forest inventory program for many reservations (Vandendriesche). Some of these inventories go back 30 or even 40 years. Information from these long-term remeasured inventories are essential for long-term monitoring.

As we move into the twenty-first century, technology will continue to change the way we view the world. Before looking to the future, it is often good to reflect on where we started. For a humorous, enlightening look on how FVS has evolved, we recommend you take a trip down memory lane (Johnson). After gaining that historical appreciation, you may be interested in what the future holds. One thing is for certain, Geographic Information Systems will play an ever-increasing role in our analysis tool-kit. Take a look at how California integrated satellite imagery, GIS, FVS, and inventory data to study the potential cumulative impacts of timber harvest on habitat suitability and the connectivity of late successional forests in northwestern California (Eng). Learn how individuals at the University of Washington are collaborating with the U.S. Forest Service to develop fully integrated software that links GIS with state of the art visualization software (McCarter). If a picture speaks a thousand words, take a peek at how stand visualization software linked to FVS is being used as a communication tool to demonstrate stand structure-fire hazard relationships (Landram). Read about how some consultants in Fort Collins, CO, are linking GIS and forest growth simulation to sophisticated spatial statistics software called FRAGSTATS (Berry and Buckley). Such collaborative efforts are bringing us the resource management tools to take us into the next century.

We hope we have peeked your curiosity about this proceedings. If our objective is technology transfer we hope yours is to learn something new. As T. S. Elliot so eloquently stated: "We shall not cease from exploration, and the end of all our exploring will be to arrive where we started and to know that place for the first time."

This proceedings presents just a sample of how FVS is currently being used. The U.S. Forest Service and its ever-widening circle of FVS collaborators will continue to improve the suite of models and tools that make up the Forest Vegetation Simulator. In a few years it will be worthwhile to convene for a second FVS conference so that we may share our experiences, our lessons learned, our triumphs, and our failures.

This first Forest Vegetation Simulator Conference and its resulting proceedings are dedicated to Al Stage. Without Al's vision, none of these papers would ever have been written.

Richard Teck, Melinda Moeur, Judy Adams

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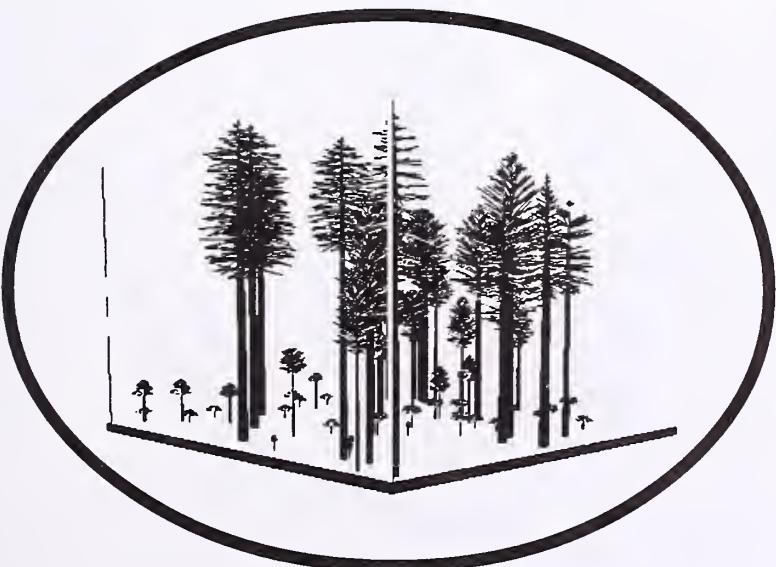
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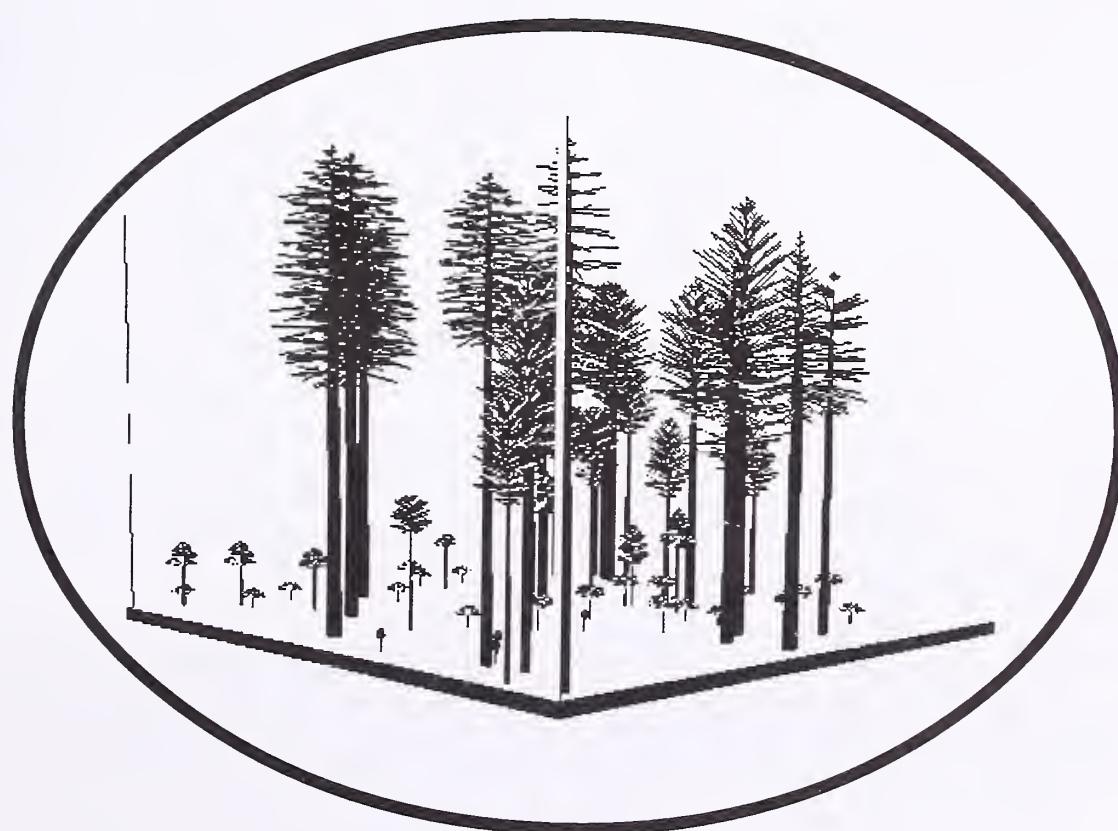
A Historical Perspective of the Forest Vegetation Simulator

Ralph R. Johnson

Abstract—The author looks back on two decades of personal experience and impressions of Prognosis history and reviews U.S. Forest Service involvement. He pays homage to the many researchers and land managers whose accumulated work over this time has brought us to today's Forest Vegetation Simulator.

I came on the Prognosis scene back in the winter of 1978. I remember this well as we left Redding, CA. My wife and two sons jammed into a Ford Pinto station wagon along with our two goldfish and the cat. I was in the old Ford pickup packed with our house plants and season's worth of canned goods. The fish were later discoved frozen in the tank as we embarked for the night in Coeur d'Alene, ID. The house plants were a total loss, black stubs in a cardboard box. I recall the temperature was around -30 when we pulled into Missoula, MT. My boss for the next few years was Dick Deden. He explained that my job was to build a new version of the Prognosis model for eastern Montana. I being a bright young biometrician should surely be capable of this task.

To set things off, Jim Laux, Dick, and I were to leave by car the next morning for Moscow, ID, to meet Al Stage and Bill Wykoff, the prime movers of the North Idaho Prognosis Stand Development Model. Dick was at the wheel for my first experience of winter driving in Montana. But I was enthralled with the likes of the Rose Lake Cafe, the second growth stands of the Idaho Panhandle, and the fear of wheeling around on a sheet of ice. Both Bill and Al were agreeable to work with me and were resigned to the dismal task of transfering their knowledge. I was shown a Deckwriter computer terminal on "the Landing" at the Moscow lab. Little was I to know this would be my roost for the next year. There would be hundreds of trips up the flight of stairs to Bill's desk to review various fits of the internal equations. Bob Monserud and I even worked out some novel approaches to height growth modeling. Dave Hamilton and I would need to process the mortality rates from some low altitude photo projects. It took a little over a year to complete this new fit of Prognosis. I learned every possible route from Missoula to Moscow and even developed a taste for Squirt (the local favorite at the Lab's pop machine).

There was no shortage of potential users, for the first round of Forest planning was well under way, and yield tables were in hot demand. Of course the Prognosis model back then was still in it's shakedown stages. We'd call that

beta testing now. The big complaint was the volume was Too High! Basal areas were way in excess of what any rational person had ever seen. So we took two approaches. One was to bound the projection with the maximum values that existed in the inventories, and the second was to try working with the mountain pine beetle model. Back then there were two moutain pine beetle camps. Burnell had one approach and Cole had the other. I was in the middle, but I felt any beetle was better than no beetle, as no field person could come up with many lodgepole pine stands that didn't at some point get nailed with a beetle epidemic.

In 1981, Dan Schoeder and I teamed up to produce the Utah and Teton models. These were the first Prognosis models to use site index. The U.S. Forest Service's Northern Region was a firm believer in Habitat Type and narry a sole had a site index curve in their field books. Most folks at the time were led to believe that in order to have a "Prognosis" model, you had to have habitat type. After more trips to Moscow and more hours on the "landing," Intermountain Region had a couple of Prognosis models each using site index. We still had the dilemna of bugs in lodgepole pine and entomologists were still arguing which approach was best.

CANUSA was going strong back in the early 1980's. There was much work on modeling spruce budworm. This was very process oriented modeling. At one point you needed to initialize the ant and bird populations. Later with the help of Tommy Gregg, this process was significantly simplified. A spruce budworm model was badly needed to help temper the excessive projections for eastern Montana Douglas-fir. Not many field people could come up with an eastern Montana Douglas-fir stand that hadn't been in a budworm epidemic.

After finishing with the Intermountain Region work, Dan and I moved over to the West Coast. Back then Prognosis was pretty much a Rocky Mountains thing and was looked on with some caution. But Pest Management (that was an OK term back then) was paying my salary, and they wanted to get a base model to hook some pest models on to. By then we had tussock moth, spruce budworm, and mountain pine beetle (using two approaches). So as to not upset the local political climate of timber yield modeling, we picked southeast Oregon as the area of interest. After sitting down with Len Volland, Walt Knapp, and some others, we decided it was only logical to make the area of application ecologically based. We picked the ponderosa pine/juniper area from the Modoc to the Deschutes. This was before the Forest Service formally coined "ecosystem management."

We saw the completion of SORNEC in 1983. This one included the impact of dwarf mistletoe and we added a point density effect to deal with clumpy pine stands. We had a futuring session in Ogden and started to use the term geographic variant to describe each of these new models. We also laid some plans for making Prognosis more modular. By

now we had lots of different volume techniques, height growth models, species lists, and the like.

From 1981 to about 1985, there was a Submittal System to hook the users up with the mainframe in Fort Collins, CO, the Univac 1184. Ron Briggs helped with this Submittal System and patterned it after one used by Bill Wykoff. A big complaint was the bill the National Computer Center printed out every time you made a run. There was a shortage of ports to get on the machine; and, in general, it was a real pain. As with SUPPOSE, we have made some major strides forward with user interfaces.

In the early 1980's there was an attempt to have the University of Idaho build a central Idaho model. This was done under the guise of the Northwest Regional Commission. The resultant work modified the underlying structure of the computer code. There was no mechanism to support the product after development so it pretty much died on the vine. I did some work in 1983 and 1984 with Bill Farr from the Juneau Lab to build a Variant for southeast Alaska. This was our first attempt to extend the logic for the Regeneration Establishment submodel and was only possible with the help of Dennis Ferguson of the Moscow Lab.

To fully utilize the Regeneration Establishment module and the new Event Monitor developed by Nick Crookston, the base operating system was enhanced. The Cover extension developed by Melinda Moeur was added as well. As I recall this was Version 5. In the fall of 1985, I moved to Fort Collins to head up the growth and yield staff of the Mensuration and System Development Staff—later called the Timber Management Service Center then still later, to be politically correct, the Forest Management Service Center. Gary Dixon was our programmer along with Kathy Sleavin. The two of them were sandwiched into the room next to the "vault" in this building. It was cozy to say the least. FHTET was still MAG and had recently relocated to the Craddock Building. Its pest model mission was not yet defined.

With personal computer technology advances and a need to get a handle on program maintenance, we set up a year's project to rewrite Prognosis into Fortran 77. This took over a year to accomplish and resulted in Version 5.2. A lot of hair pulling and debugging to rectify the bugs created and uncovered by this process was sure worth the stress. The "Mother Code" was moved from Moscow to Fort Collins. One could Run Prognosis on most computers including a PC.

With the addition of the Klamath Mountains Variant came sprouting logic. This was a biological necessity to handle tanoak regeneration. Shortly after followed the WESSIN Variant. This tapped into the modeling work done by Bill Oliver and Leroy Dolph. Leroy added a different approach to the way relative density was modeled.

To assist the Black Hills with their Forest Plan revision, an effort was made to incorporate the GENGYM models into Prognosis. GENGYM is a diameter class model and considerable effort was made to assure that repackaging the equations into an individual tree model would in fact work. Many hours were spent with Carl Edminster to show the accuracy of this approach. This also showed there was some refitting needed to some of the GENGYM models too! The UNIVAC bill was still a nagging concern, so we moved the code to the Data General.

In 1991 we added Richard Teck to the staff. Rich had been working on NE-TWIGS for the Northeastern Forest and Range Experiment Station. With Rich's help we built the NE-TWIGS Variant. Renate Bush came as a trainee biometrician. Jim Brickell and Renate refit the models for the Kootenai.

A suggestion was then made to weave in the Lake States and Central States TWIGS models. Wow! Did this land us in the world of Mid-West politics. It was clear the word Prognosis by now had a lot more meaning and baggage. Rolfe Leary was pretty emphatic that TWIGS was not a Prognosis. After showing that the simulations were accurate using TWIGS equations in a Prognosis framework, the need was clear to somehow give author credit to the scientist(s) developing the models, yet portraying to the users there was but one system. We made the change in terminology to FVS. The Forest Vegetation Simulator. Each variant was described as FVS with a GENGYM or TWIGS or Prognosis model.

We're still doing some mopup by adding geographic variants like the West Cascades, PN-Coast, central California, and the Southeast. Perhaps the more interesting work has been the use of FVS in projects and assessments. There is an ever present need to reflect accurate insect and pathogen impacts to Forest growth. These changes to the Forest have direct effects on wildlife habitat, fire regimes, and aesthetics. The model runs in a fraction of the time on a Pentium PC as compared to the old UNISYS 1184. One can see visual displays of the Forest over time though the use of Bob McGaughey's Stand Visualization System. I've only spotlighted a few of the many successes of this system.

In addition to the scientists at Moscow, there have been numerous other individuals who have proved invaluable in the development of FVS. Bob Cottingham and Ron Hamilton at the Ogden, UT, office were strong proponents of using SDI. As a result we utilized Jim Long's stand density work. Ralph Warbington of Sacramento, CA, added the California crown width equations. George Lightner did much of the work on the Blue Mountains variants. Dennis Donnelly added the PN Coast. Bob Eav will add to this list with those individuals working on the insect and disease models. I thank you for your continued ideas and critiques. They are what continually make the product better.

Software Demonstrations
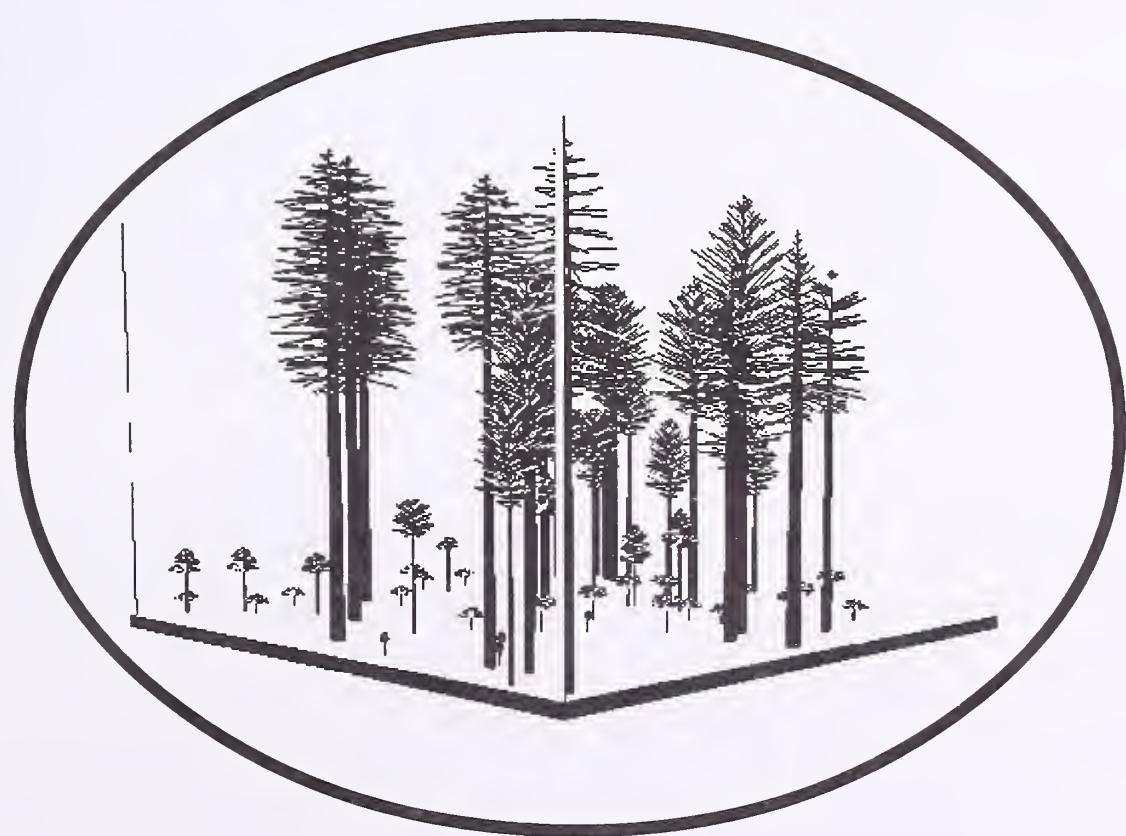
Suppose: An Interface to the Forest Vegetation Simulator

Nicholas L. Crookston

Abstract—Suppose—a graphical user interface for the Forest Vegetation Simulator—simplifies the task of simulating the changes in forest vegetation for a long timespan and a landscape spatial scope. This introduction of Version 1 of Suppose presents the system's goals and the applications in forestry it addresses. It illustrates the process of using Suppose, describes the input and output data, summarizes the program's features including those planned for future versions, and describes how you can get your own copy. Suppose runs under Windows 3.1, Windows 95, and Version 4 of AIX, IBM's version of Unix.

Suppose is a graphical user interface for the Forest Vegetation Simulator designed to simplify the task of simulating changes in forest vegetation for a long timespan (100 to 400 years) and at landscape spatial scope between one and about 1,000 forest stands. This paper introduces Suppose by presenting its goals and its applications in forestry, illustrating the process of using Suppose, describing the input and output data, summarizing the program's features including those planned for future versions, and describing how you can get your own copy.

The Forest Vegetation Simulator (FVS), also known as the Prognosis Model (Stage 1973; Wykoff and others 1982), was designed to make consistent forecasts of forest stand development across a broad range of planning scales. The model's original name, the Prognosis Model, reflects the idea that knowledge of current forest conditions and how forests change can be used to predict future forest conditions. The name Suppose implies a desire to comprehend what the future conditions would be given some proposed management plan or a proposed policy governing how management choices are made along the way. Suppose is an interface that includes the key element of allowing proposed management plans or policies to be entered into the FVS system using methods that are much more directly related to forest management than using the FVS keyword system directly.

Suppose runs under Windows 3.1, Windows 95, and Version 4 of AIX, IBM's version of Unix. It was built using a portability tool kit (XVT Software Inc. 1995) using the C++ programming language.

Suppose Applications

In summarizing the scope of applications for and components of FVS, Teck and others (1996) pointed out the importance of understanding how forest vegetation will change in response to natural succession, imposed disturbances, and proposed management actions. How such changes affect ecosystem values is relevant to today's forest management. FVS answers these questions by providing a synthesis of scientific knowledge about important ecosystem components and a means for integrating the knowledge in a format useful to resource managers.

Suppose goes further than FVS alone in providing means for achieving FVS's own application goals in a few important ways:

First, simulating many stands with Suppose is nearly as easy as simulating an individual stand. Suppose allows groups of stands to be set up and manipulated using exactly the same tools and methods used to manipulate individual stands. For example, say a landscape is represented by a set of stands that have been grouped by management class, condition class, forest type, or a combination. All the stands in the landscape can be entered into Suppose at once. Then the management actions are set up for each group, treating the groups as entities, rather than setting the management actions for each stand separately. Suppose's support for the FVS Event Monitor (Crookston 1990) helps facilitate this approach. While this capability is provided by the Parallel Processing Extension (PPE) of FVS (Crookston and Stage 1991), it is not often used because it is difficult to set up the simulations in the PPE.

Second, Suppose places FVS and its extensions more firmly in an ecosystem analysis framework. The timeframe and spatial scope of an ecosystem plan are easily defined. Next is the specification of ecosystem components represented by FVS extensions. Then, management actions that act on the ecosystem components are defined. A flexible report generator makes it easy to organize output to highlight important decision variables. The resulting package of features is an integrated program that supports flexible, realistic ecosystem simulation and adaptive management (Holling 1978).

Third, Suppose goes much further than FVS alone in meeting resource managers on their turf, rather than on a computer's turf. The amount of detailed computer system knowledge is reduced using Suppose as compared to directly interacting with FVS keywords to set up simulations. The Suppose management screens, for example, use terms that are taken directly from Smith's (1962) text on silviculture and from recent additions to the practice of silviculture.

Version 1 of Suppose does not contain all planned features but it does contain enough to make it useful for land managers.

Using Suppose

Suppose first presents the Selections Window (fig. 1), which provides direct access to the most fundamental features of Suppose. Operation then follows these basic steps:

1. Specify the spatial scope of a simulation by picking the stands to include in the simulation. This is accomplished by using the Select Simulations Stands window (fig. 2) to list the available stands and to pick any set of stands for the simulation. The available stands are those from one or more locations or in one or more groups listed in the window. Locations and groups are designated in the Suppose input data, described in the following section, "Inputs and Outputs."

2. Specify the temporal scope using the Set Time Scale window (fig. 3).

3. Use the Management Actions window (fig. 4) to select a category of actions, then a specific action. For each action, a specific window is used to customize the action for specific needs. Figure 5 is an example of the one-entry shelterwood window. The scheduling of the action can be done for a specific year, or it can be scheduled to occur when a condition is detected by FVS. Default conditions exist for each management action. Each can be customized to meet specific needs.

4. Once the stands are selected and desired optional settings are done, the simulation is run by pressing the Run Simulation button on the selections window (fig. 1). The direct insertion of FVS keywords, the specification of FVS post processing programs, or both, can be done prior to running the simulation.
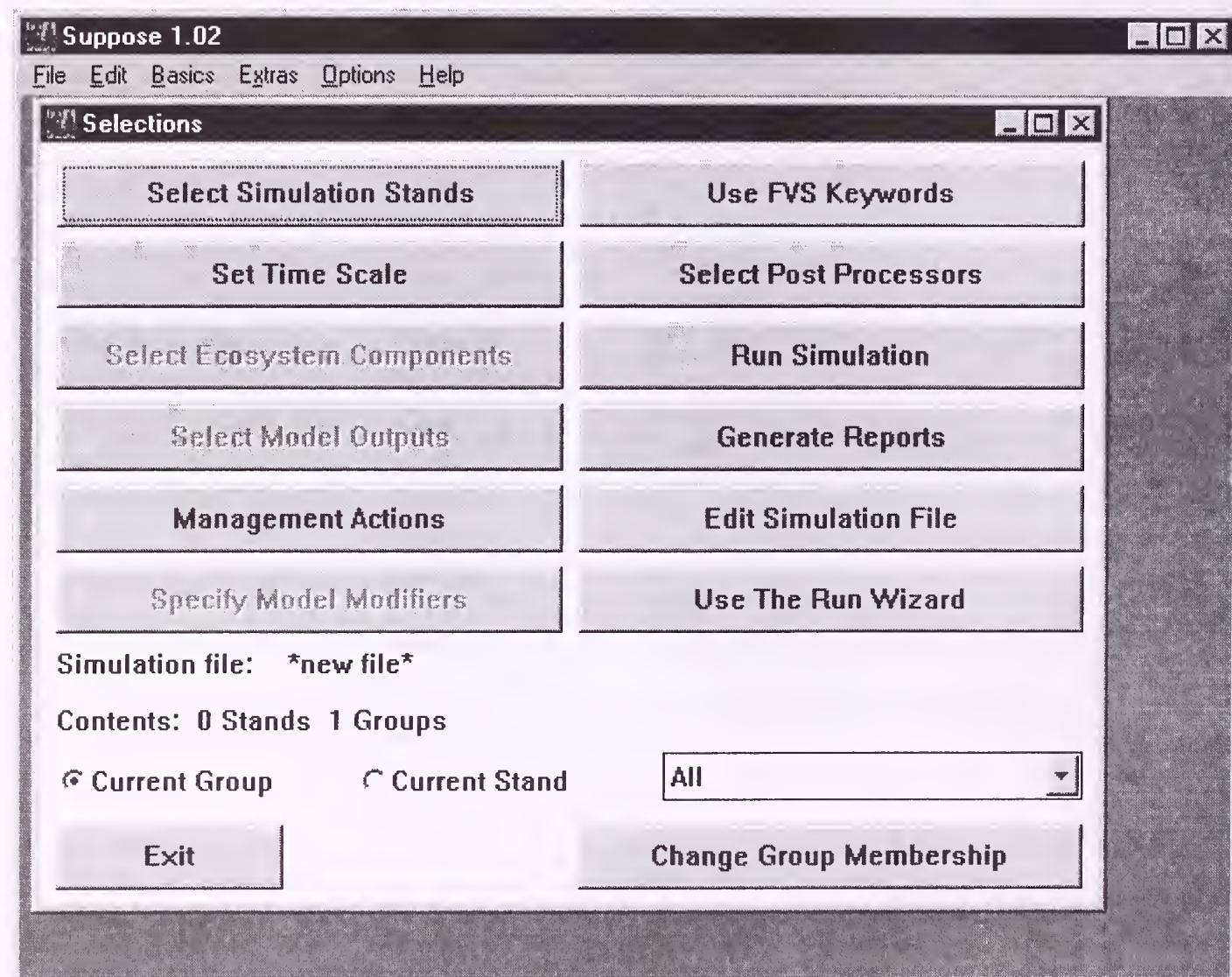
Figure 1—The first window of Suppose is the Selections window. The organization of the window follows the sequence of steps used in ecological modeling. Features that are planned but not yet implemented are "grayed out."
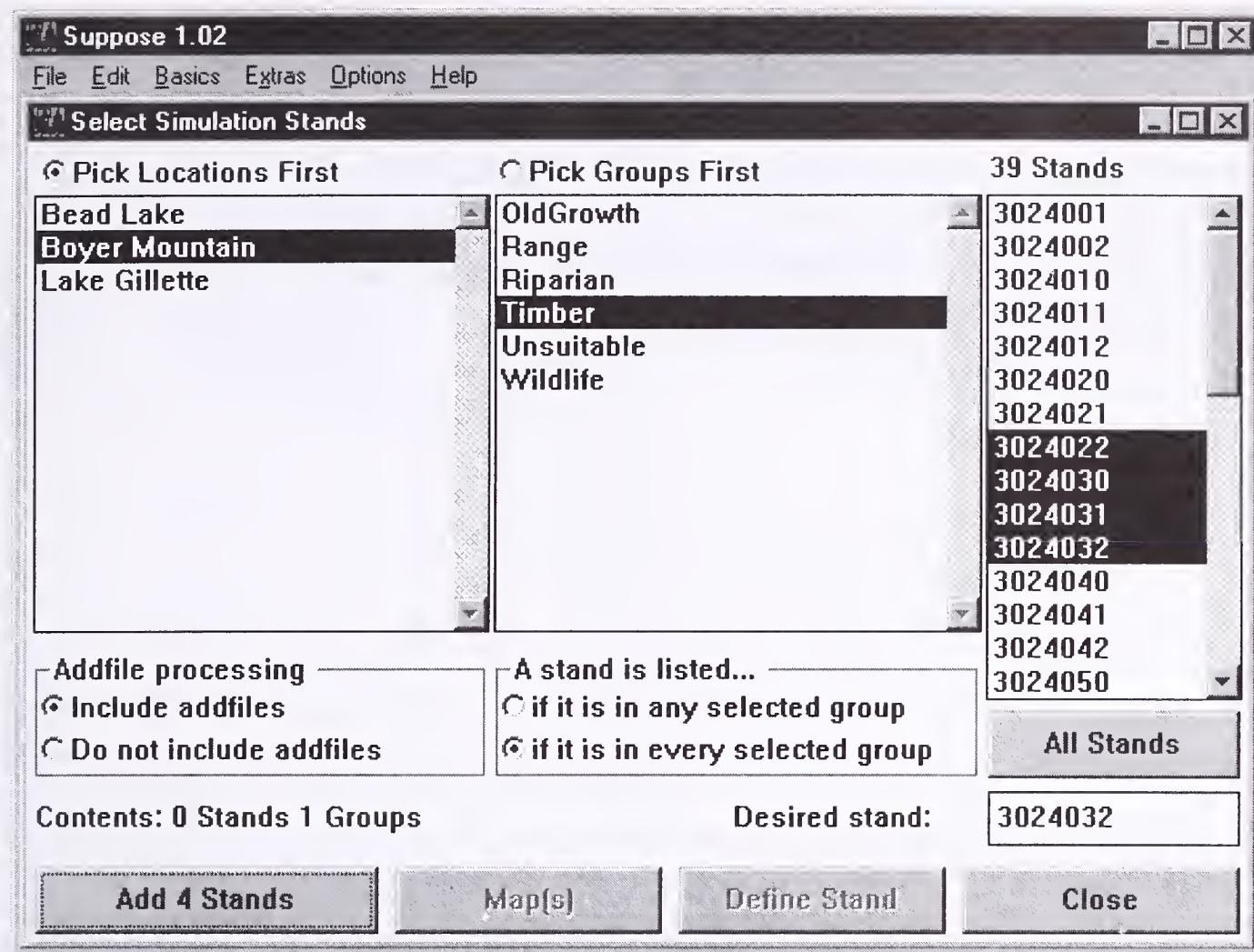
Figure 2—Specification of the spatial scope of a simulation is done using the Select Simulations Stands window.
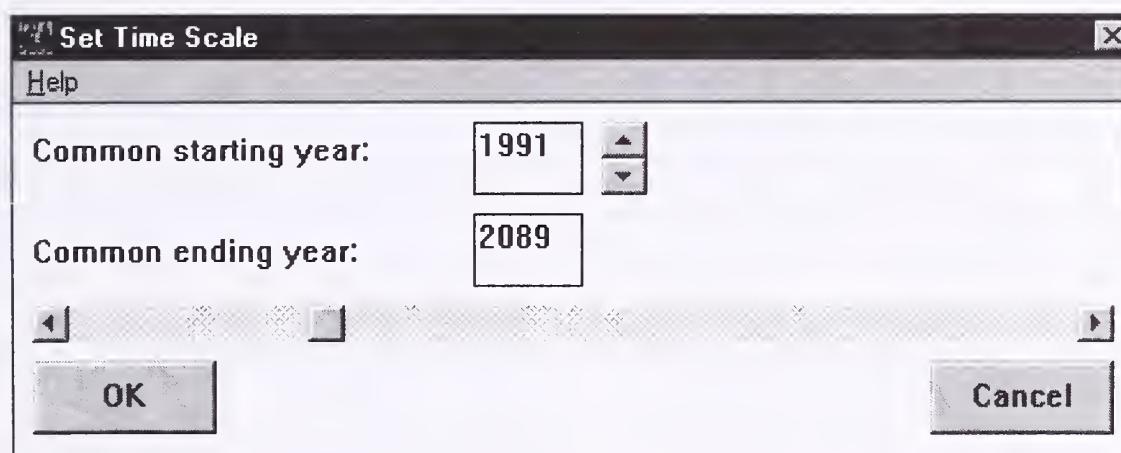
Figure 3—The temporal scope is specified using the Set Time Scale window.
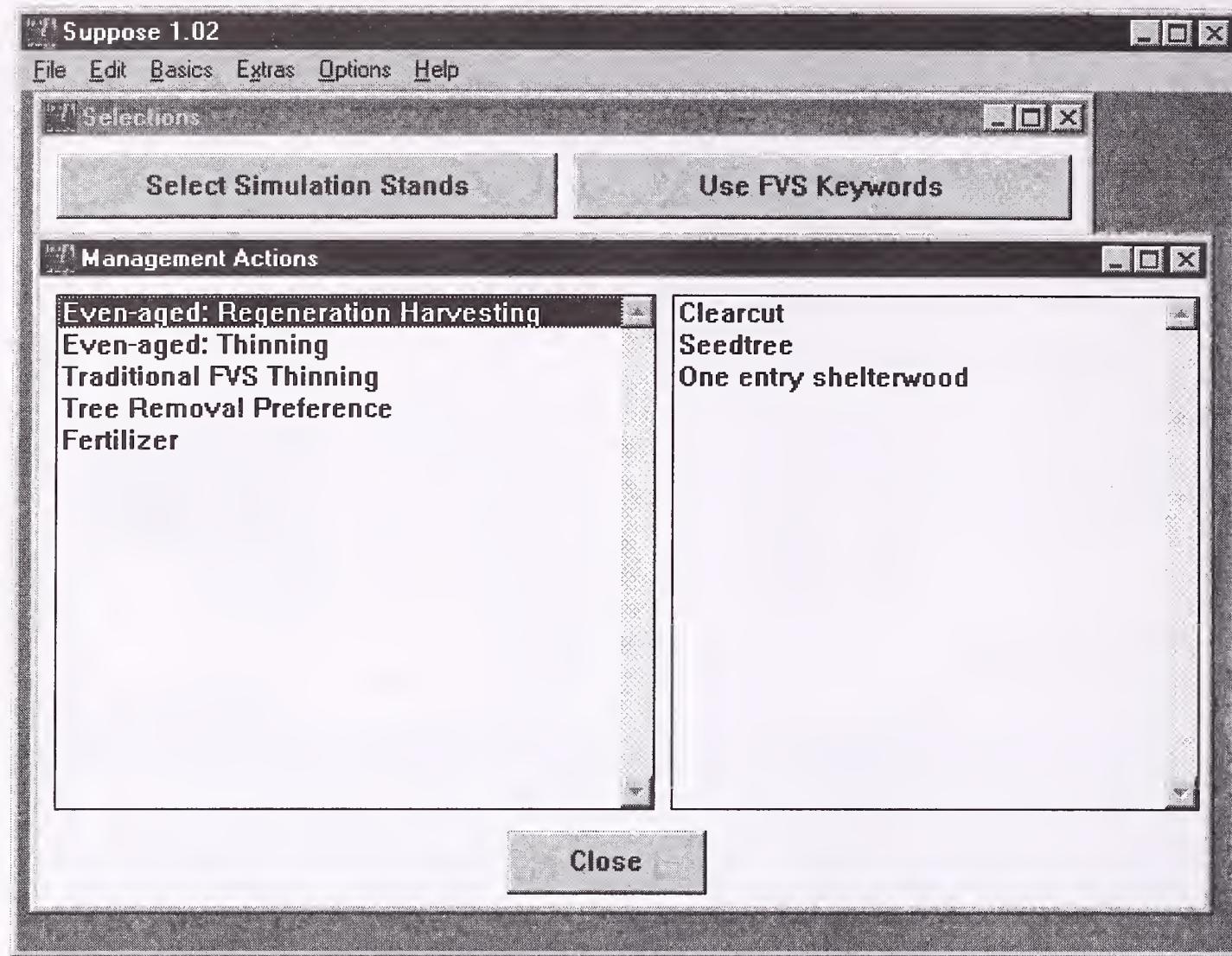
Figure 4—This is the current Management Actions window. A planned addition to Suppose
will include a much richer set of management actions.

5. FVS output can be viewed in a spreadsheet-like format using the Suppose Generate Reports window (fig. 6). The contents of this window can be copied to the Windows or Motif clipboard and pasted into other programs such as word processors and spreadsheets (fig. 7). Suppose can also create a standard text file that contains these data. In addition, the FVS-generated output can be printed or viewed using other tools.

Suppose contains many other features besides those illustrated here. See the "Feature Summary" section for a list.

Inputs and Outputs _____

Suppose accesses lists of stands that are available for inclusion in a simulation using a simple data file called the Suppose Locations File. This file contains one data record for each location. A location is defined to be any geographically related set of stands, such as those from a given watershed, mountain, or butte. One of the data elements for a location is the name of another data file that contains information about all the stands at the location. This second data file, called the Stand List File, is described below.

A location does not have to contain a set of contiguous stands. For example, a location may be the name of a State and the Stand List File filled with a collection of the forest inventory plots for the State. These files are provided to Suppose, and their contents depend on the application. Usually, the file will be provided by a central office or generated using data access tools developed for the institution. In some cases, Suppose will be part of a larger analysis system, such as is planned for INFORMS (Williams and others 1995), that generates the locations and stand list files automatically.

Each record in the locations file refers to another file called the Stand List File. The contents of the latter file include data entries for each stand at the location, including the identification of the stand, site data, the name of the FVS-ready tree data file (Suppose does not read this file, but it does provide FVS with this name so that FVS can read it), identification of the geographic variant of FVS that should be used to simulate the stand, and the identification of groups to which the stand belongs. These grouping codes are presented in the Select Simulation Stands window (fig. 2) and are used to facilitate manipulating groups of stands as well as individual stands. As with the Locations File, the
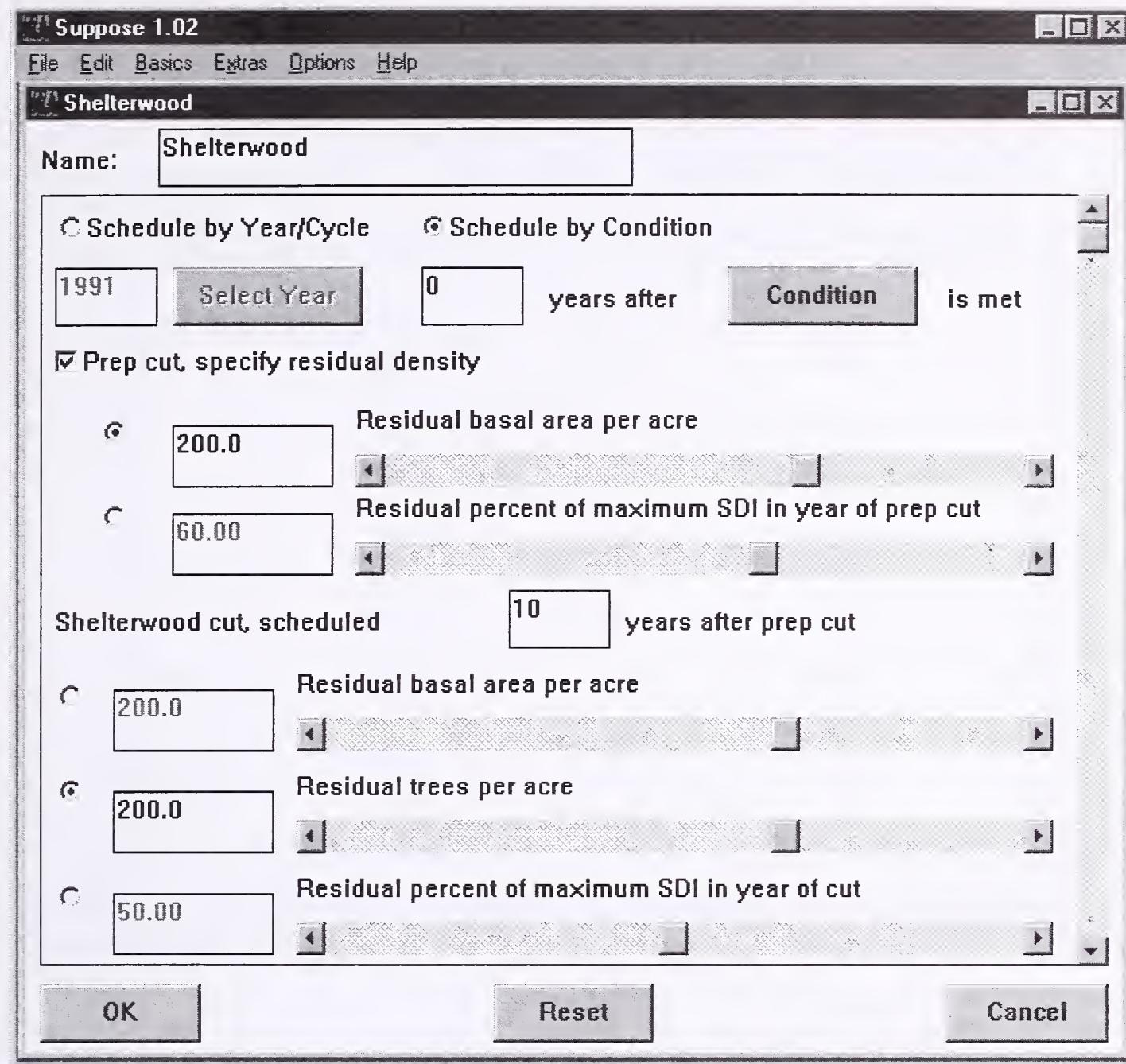
Figure 5—The one-entry shelterwood window is an example of Suppose management windows. Not all the parameters fit on the screen, but a vertical scrollbar takes the user to additional items. The scheduling of the action can be done for a specific year, or it can be scheduled to occur when a condition is detected by FVS using the Schedule by Condition feature.

details of this file's content are in the Suppose on-line help system.

The output from Suppose is a simulation file that is interpreted by FVS as a keyword file. This file is read by FVS, along with the tree-level inventory data, so that FVS can make the projection.

Feature Summary for Version 1 of Suppose _____

- Views analyses in the same terms as those used in building ecological models.

- Provides an interface to FVS that uses the terminology of forest resource management.
- Provides the ability to change (edit) already created simulation files using the same tools used to initially create them.
- Automatically adapts itself to geographic variants, including variants such as the British Columbia, Canada, variant that uses metric units.
- Automatically invokes the FVS program that contains the geographic variant and extensions needed to make the simulation.

11

Suppose 1.02

File Edit Basics Extras Options Help

Generate Report (Proto Type)

Title: Example run   Type: List over years

Cases: c4:EXAMPLE.out:Stand=3024032:Mgmt=Shlt:Groups=[ALL, TI ▼]   Clear Cases

Year	c3:TCuFt	c3:TpTCuFt	c4:TCuFt	c4:TpTCuFt
1991	5065	5065	5882	5882
2001	5921	5921	6837	6837
2011			7776	
2011	6749	6749	7505	7776
2021	7578		8327	
2021	7467	7578	8034	8598
2031	8022	8133	8755	9319
2041	8895	9006	9688	10252
2051	9793	9904	10648	11212
2061	10611		11530	
2061	9104	10722	9572	12094
2071	9549		10210	
2071	9456	11167	9913	12732
2081	9730	11441	10443	13262
2091	10561	12272	11318	14137

Write Report   Clear Report   Read FVS Output   Close

Figure 6—Suppose report window provides FVS output variables in a spreadsheet-like format designed to compare variables from different "cases." A case is a simulation of one stand under one set of options. In this figure, standing total cubic volume and total production are tabulated for case "c3" and "c4" in a format designed to be transferred to a spreadsheet program (fig. 7). Blank fields are present in the table when two lines are needed to display data for one case and not another. In this example, harvests were simulated in different years in each of the cases necessitating two lines for years 2011, 2021, and 2071.

- Can be customized to meet the needs of various institutions, agencies, and users. Most of this customization can be done without program recompilation.
- Provides for making simulations that contain many stands using the same tools used to make simulations of single stands.
- Provides for grouping stands in a simulation and treating the groups as entities.
- Provides all of the power of FVS—none of its features are left out or inaccessible (with the exception of direct support of the PPE, see "Future Versions" section, below).

- Provides full featured on-line help with cross linkages to definitions and related help topics.
- Includes a built-in tutorial to aid in learning how to use the program.
- Provides a handy step-by-step guide to routine tasks.
- Provides tools that allow for routine use of FVS without knowing the FVS keyword language nor remembering the details of keyword usage.
- Runs as a stand-alone tool or cooperatively with other tools such as INFORMS (Williams and others 1995), data bases, Geographic Information Systems, spreadsheet programs, and word processors.
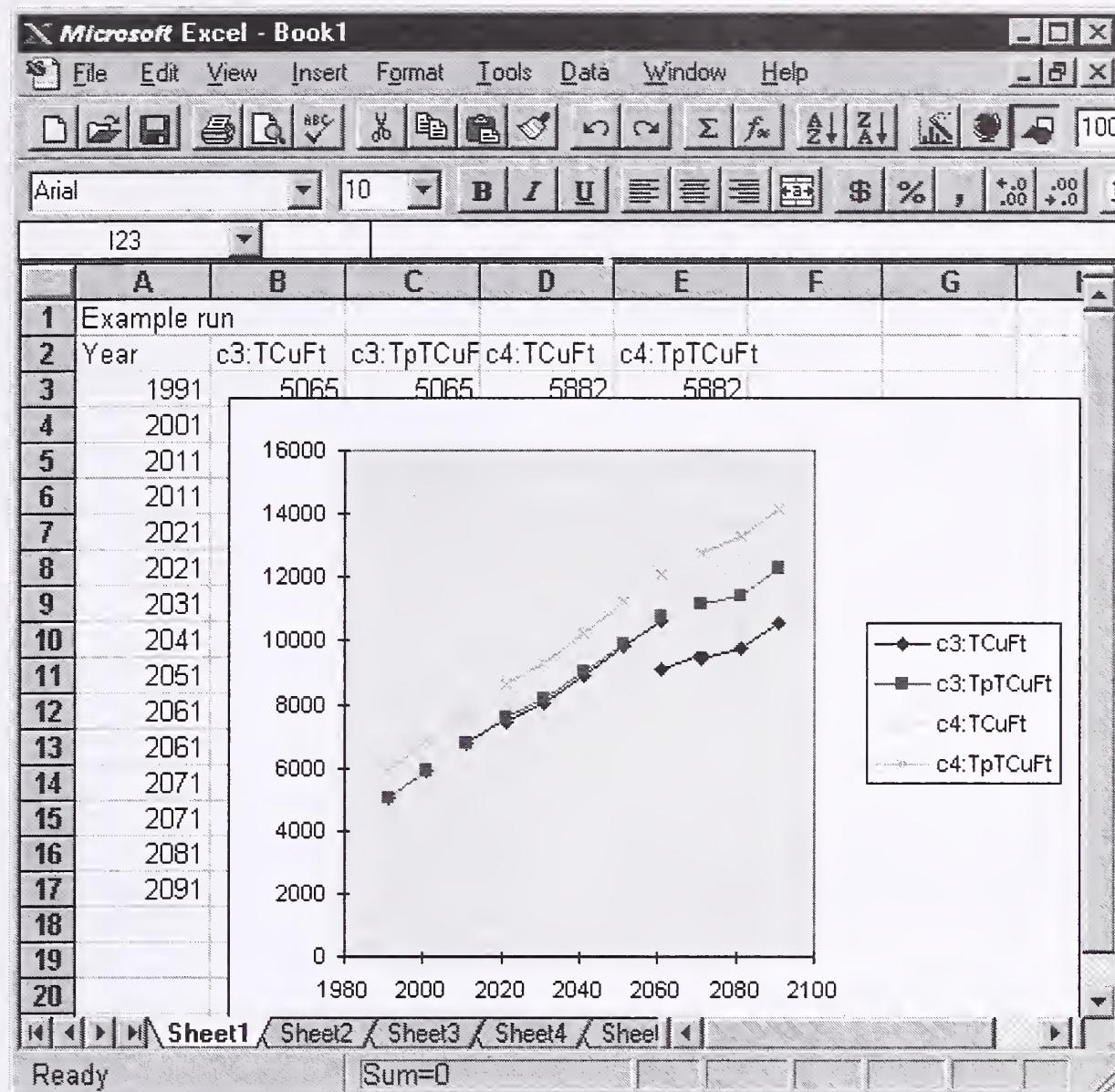
Figure 7—The data from the Suppose report window can simply be transferred to other programs for generating graphs or inclusion in reports.

Future Versions and Planned Enhancements

- Build the three remaining key parts of Suppose designed to more simply support FVS extensions, provide tools to customize the component models, and provide tools that ensure desired FVS output reports are produced.
- Add more management actions and improve the schedule by condition rule library.
- Improve the on-line help and tutorial.
- Improve the Generate Reports facility to allow it to build many more report types. Currently, this facility only presents data listed by year. Provide the ability to list variables by case (a single simulation or a weighted average of simulations) and by species, tree size class, or for individual tree attributes. Also, output a pseudo-English description of the progress of selected simulations and provide graphic outputs.
- Rebuild the Edit Simulation tool so that it is more intuitive and informative.
- Provide support of the PPE (Crookston and Stage 1991).
- Provide automated installation procedures.
- Strengthen, simplify, and more completely document the C++ source code insuring the long-term maintainability of the program.

How to Get Your Copy _____

To get a copy of Suppose, program an Internet Web browser with this URL:

> ftp://forest.moscowfsl.wsu.edu/suppose

For Windows 3.1 or Windows 95, get:

> readme.dos—contains installation instructions and some related information.
> suppose.zip—contains the program and a few test data sets.

For IBM AIX, get:

> readme.aix—contains installation instructions and some related information.
> suppose.tar.Z—contains the program and a few test data sets.

Interactive anonymous FTP is also supported at this address: forest.moscowfsl.wsu.edu.

The program is also available from the author at this address:

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British Columbia's Forest Vegetation Simulator Application Software

Barry Snowdon

Abstract—The British Columbia Forest Service has recently built a suite of Windows based tools to enable its diverse client base to conduct FVS runs in a user-friendly computer environment. The tools are (1) DATAprog—a generic treelist builder/data translator; (2) SIMprog—a single stand, "keywordless" simulation tool that is designed for silviculture gaming; and (3) flexible tabular and graphical reporting tools. The rationale, functionality, and future development direction of each tool is discussed.

The Province of British Columbia's Forest Practices Code legislation requires that forest managers know the growth and yield, and forest health implications of proposed silviculture regimes, at both the stand and forest level. The predominant management regime in British Columbia is clearcut logging of the "naturally occurring" stand followed by planting of desirable species. The Province has developed separate growth and yield applications to simulate the development of the naturally occurring and planted stand. They are the "Variable Density Yield Projection" model (VDYP) (Smith 1990) and the "Tree and Stand Simulator" (TASS) (Mitchell 1975), respectively. Both models assume an even-aged stand structure. Furthermore, TASS assumes a single species stand.

Despite the predominance of even-aged management, British Columbia manages approximately one million hectares of interior Douglas-fir under selective logging. Currently, the Province does not have a growth and yield tool to assess the probable future development of these stands. The North Idaho variant of the Forest Vegetation Simulator (FVS) (Stage 1973) has been chosen for adaptation and implementation in British Columbia to address this need.

The British Columbia Ministry of Forests (MoF) has embarked on a major effort to calibrate the North Idaho variant for the Southern Interior of the Province. Once calibrated, the model's successful implementation will depend upon (1) convincing the user that it is worth the time and expense to conduct a ground based inventory (TASS and VDYP can be initialized using existing aerial inventories); and (2) the user's facility with the model (that is, entering data, conducting simulations, and interpreting the results).

Since 1996 the B.C. Ministry of Forests has built a suite of Windows based tools to address this second issue. Each product has been written in Microsoft, Visual Basic, Version 4.0 and run on Windows 3.11, Windows 95 and NT operating systems. The minimum hardware requirement is a 486 personal computer with 16 mb of RAM. The software tools are (1) DATAprog—a generic treelist builder/data translator; (2) SIMprog—a single stand, "keywordless" simulation tool that is designed for silviculture gaming; and (3) flexible tabular and graphical reporting tools.

DATAprog—A Generic Data Translator

The impetus for the data translator came from discussions between Nick Crookston (U.S. Forest Service, Intermountain Research Station), Fred Martin (Washington Department of Natural Resources) and Barry Snowdon (B.C. MoF, Forest Practices Branch). If the data source for the creation of treelists is a corporate database, a customized data translator can be written. However, such a translator does not address a diverse group of users (private industry and consultants) each with their own specific inventory data formats. The generic data translator was built with a diverse client base in mind.

This product only makes one assumption about the data—each measured attribute for an individual tree will reside on the same record in the data file. DATAprog can be used as a data entry tool or a data translation tool.

If the product is used as a translator, the user:

1. Imports their delimited or column based data into the spreadsheet style environment (fig. 1).

2. Selects a column of data, assigns a measurement type and the unit of measurement (for example, column A is d.b.h. and the unit of measurement is cm) (fig. 2).

3. Identifies and excludes rows containing headers and footers or other extraneous comments.

If the tool is used in data entry mode, users are presented with a blank spreadsheet into which they can enter data.

In either mode, rows can be excluded on the basis of row number or a search string. The spreadsheet style environment has full editing capabilities (including "search and replace"). DATAprog will automatically validate the contents of all assigned columns. Once the user has identified all relevant columns of data, identified extraneous rows and made other editing changes, the "translation format" can be saved as a "template." This template can then be used to translate other data files with the same format.

DATAprog can be used to convert "metric" units into "English" units, B.C. measurement codes to USFS codes, and/or the reverse. Hence, DATAprog can be used to convert
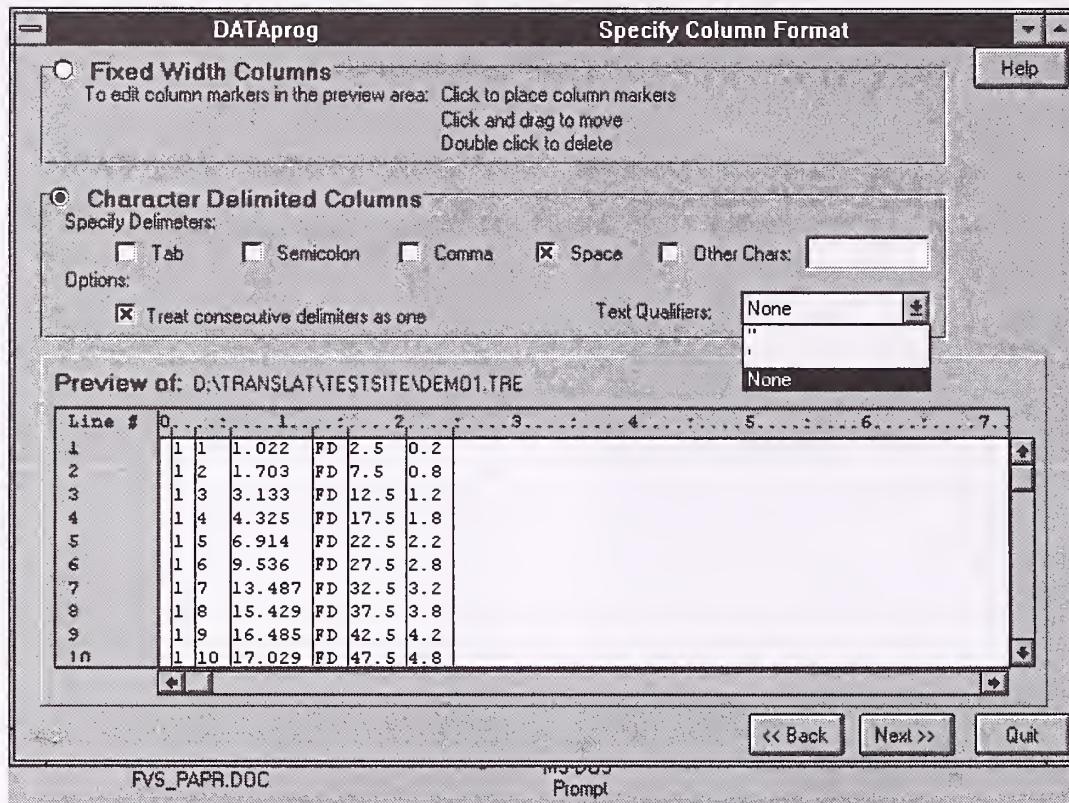
Figure 1—Specifying the column format using DATAprog.
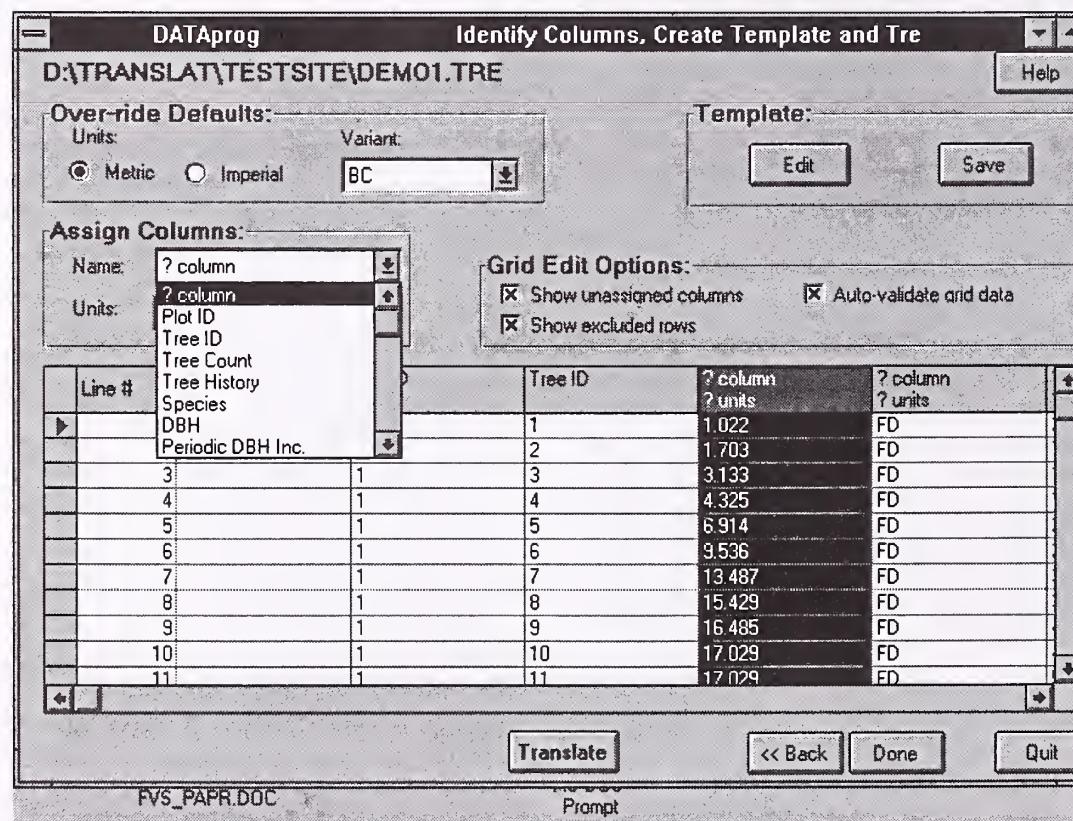
Figure 2—Assigning measurement type and units to columns of data using DATAprog.

B.C. treelists to U.S. treelists or U.S. treelists to B.C. treelists. The product can be used to convert a projected treelist into an input treelist.

In addition, DATAprog can be used to edit either new or existing SUPPOSE "Stand List Files" and "Location Files" (Crookston, this proceedings).

SIMprog—The "Keywordless," Stand Level, Simulation Tool _____

United States users may ask: "Why not use SUPPOSE?" While SUPPOSE is a useful tool for landscape level analysis, this capability imposes a considerable overhead (in complexity) when gaming with individual stands. To reduce this complexity and to customize the simulation tool to B.C.'s needs, the Ministry of Forests decided to create its own stand level simulation tool.

SIMprog has the following functionality:

1. The user can build keyword files without any knowledge of keywords. The site descriptors, inventory design, volume limits, simulation length, regeneration assumptions, and silviculture regimes are input through a series of screens accessed via drop-down menus. A group of keywords built via a single screen will be referred to as a "keyword set."

2. The keyword files are automatically annotated with a brief meaningful description for each "keyword set." A user can use these annotated keyword files to learn about the keywords themselves.

3. A log entry is created on the main work screen for each "keyword set." The user can at any time "click on" a log entry and will be returned to the appropriate screen to change that particular set of simulation parameters (for example, change the residual basal area for a thinning treatment) (fig. 3).

4. Menu items and screens have been built for "thin from above or below" and "thin by DBH class" silviculture treatments. Silviculture treatments can be grouped together to create a silviculture regime that can be saved for future use (fig. 4).

5. The user can enter keywords directly into a data entry grid that takes care of keyword formatting. The user can tag this "keyword set" with a brief meaningful description. This user built "keyword set" can be used in other simulations.

6. SIMprog handles all file management, the construction of the response file, and execution of the simulation.

Flexible Tabular and Graphical Reporting Tools _____

The traditional FVS output is voluminous, and apart from the "Summary Statistics" table, the rest of the output is difficult for the casual user to interpret. To address this problem, two flexible tabular and graphical reporting tools have been created. For discussion purposes these two reporting tools will be referred to as the "Custom Reporter" and the "Stand and Stock Table Generator." Both can be used to produce either tabular or graphical reports.
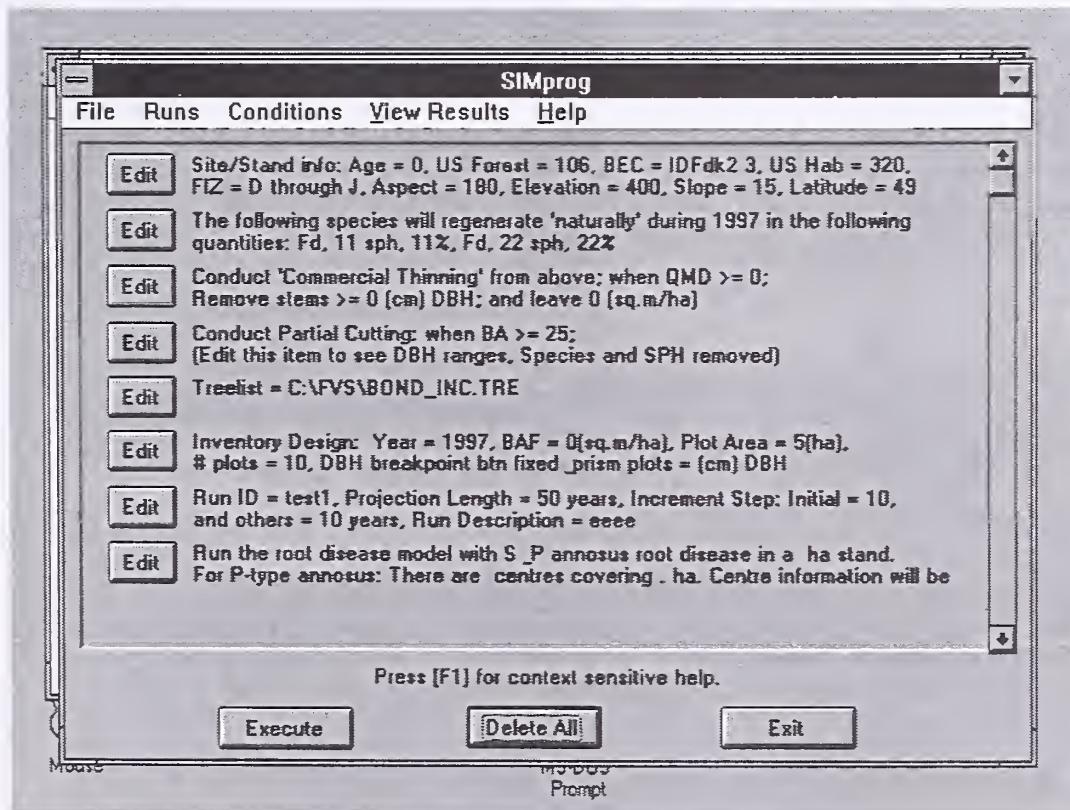
Figure 3—Automatic descriptive logging of the simulation parameters by SIMprog.
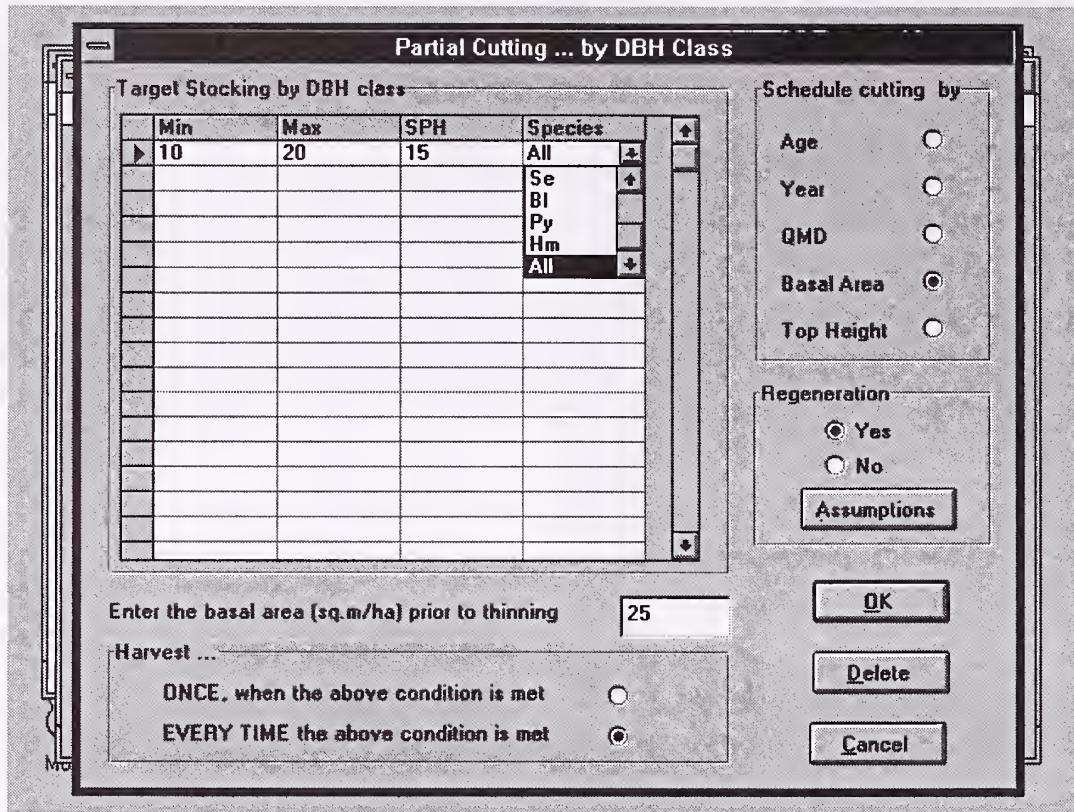
Figure 4—The SIMprog "Partial Cutting ... by DBH Class" screen.

The "Custom Reporter" has the following features:

1. Selection of any subset of variables from multiple simulations for comparison.

2. Both the results and the assumptions (the brief descriptions automatically assigned to each "keyword set") are reported.

3. The user has the option of plotting any variable against any variable for graphical comparisons.

The "Stand and Stock Table Generator" has the following features:

1. Allows the user to generate graphical or tabular stand and stock tables.

2. The contribution of each species to the DBH class total is reported.

3. DBH class boundaries can be specified by the user and need not result in DBH classes of the same width (fig. 5).

4. Stand and stock tables can be generated for both standing and harvested trees.

5. Numbers of stems, basal area, total volume or merchantable volume can be plotted against calendar year. The contribution of each individual species to the stand total is displayed (fig. 6).

Future Directions

Currently, the "Stand and Stock Table Generator" is a stand alone product; while the "Custom Reporter" is imbedded in the "SIMprog" code. The plan is to create a seamless linkage between the "Stand and Stock Table Generator" and SIMprog. It could then be accessed either as a stand alone product or via a menu item within SIMprog. If sufficient U.S. demand existed, the "Custom Reporter" would be given stand alone capabilities and both reporting tools would be enhanced to handle either B.C. or U.S. data sources.

At present, only one stand and stock table (from a particular simulation) can be displayed on the PC monitor at a time. The ability to display multiple stand and stock tables from multiple simulations is planned. In addition, the ability to display height distributions is planned.

The on-line help for DATAprog, SIMprog, "Stand and Stock Table Generator," and "Custom Reporter" is only partially complete. When complete, each product will have standard Microsoft style on-line help (that is, "Contents," "Search for Help on," and so forth) and on-line tutorials.

Finally, a metric version of the "Stand Visualization System" (McGaughey 1997) will be accessible via a menu item within SIMprog.
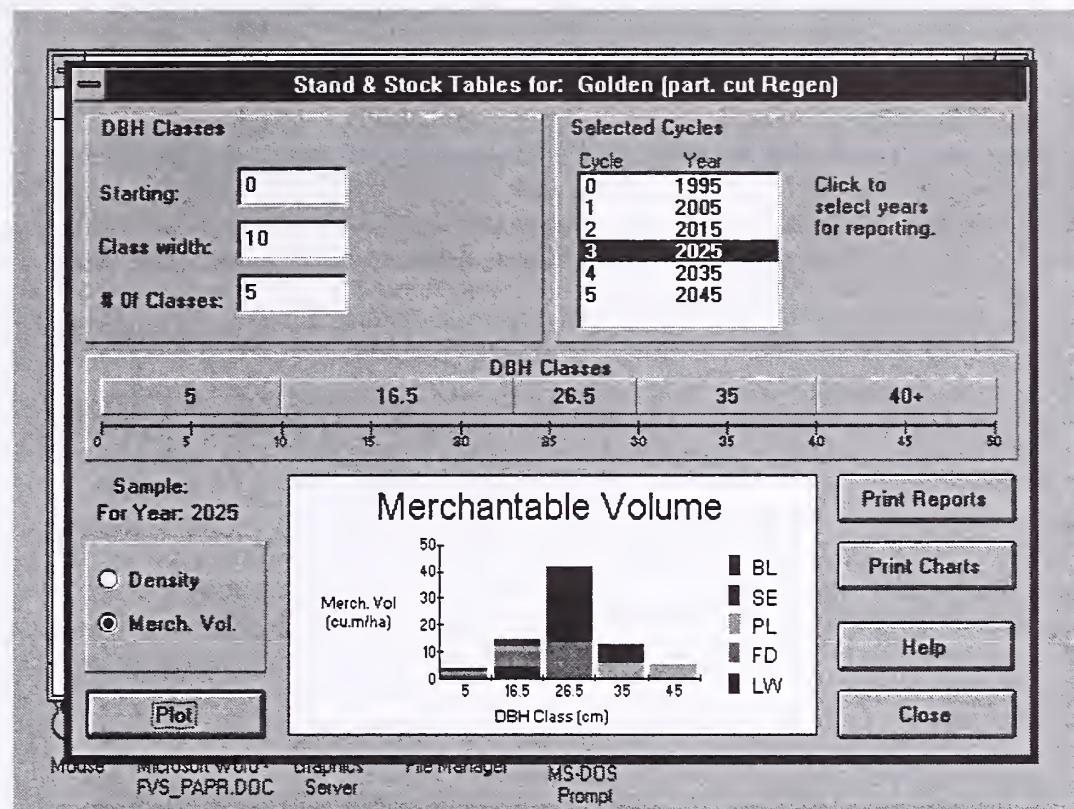
Figure 5—Specifying DBH class boundaries within the "Stand and Stock Table Generator."
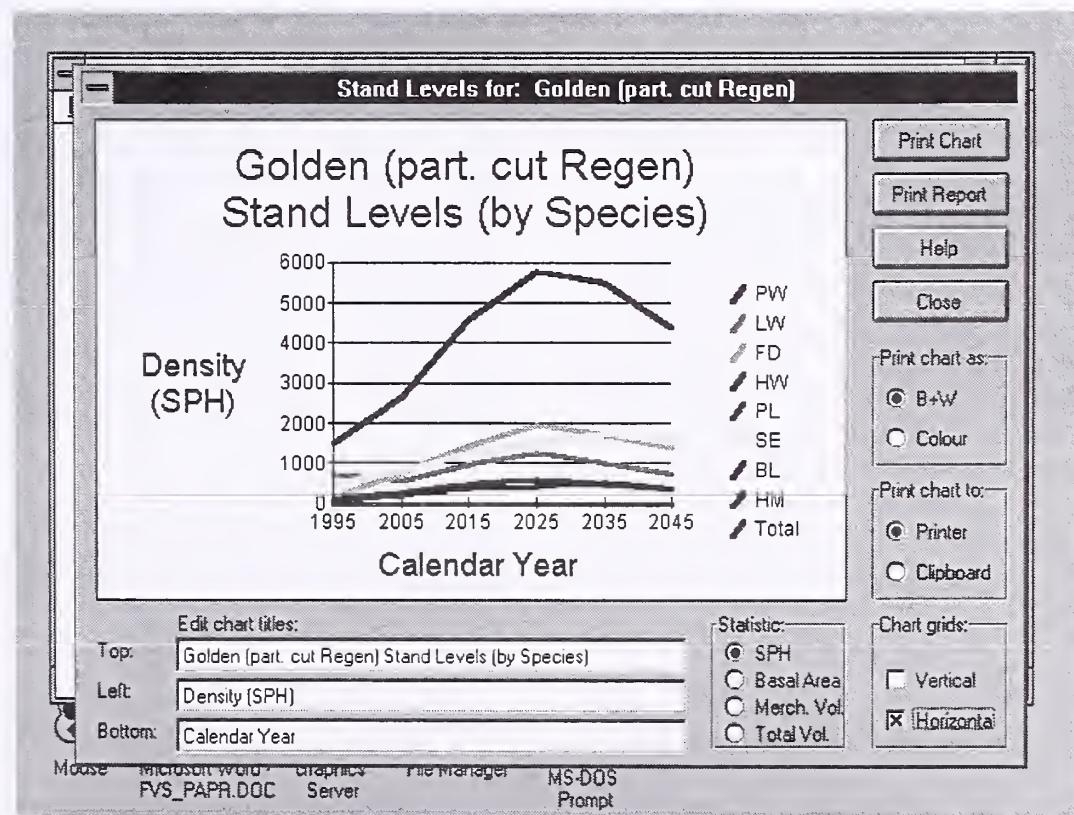
Figure 6—Reporting changes in species composition over time using the "Stand and Stock Table Generator."

Acknowledgments

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Seamlessly Linking ARC/INFO to Landscape Analysis and Forest Growth Models

Joseph K. Berry
David J. Buckley
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Abstract—The ARC/INFO system is a powerful GIS that is widely used by natural resource organizations. FRAGSTATS is an extensively used program that derives a comprehensive set of useful landscape metrics. The Forest Vegetation Simulator (FVS) is a forest growth and yield model used throughout the U.S. Forest Service. Fully integrated links between ARC/INFO and the FVS and FRAGSTATS programs through user-friendly graphical menus consist of scroll lists, toggles, and buttons to facilitate program specifications and automatically generate appropriate tables, charts, and maps for enhanced interpretation of the results. The FRAGSTATS*ARC and FVS*ARC programs control the selection of maps, access of ARC/INFO data, selection of program indices, program execution, storage of results in data base tables linked to ARC/INFO maps, and display of results in a variety of tables, charts, and map displays. The differences in spatial character of the two applications resulted in different approaches to accessing and processing the data used in the seamless link between the forest management programs and the GIS.

How will forest vegetation change in response to natural succession, imposed disturbances, and proposed management actions? How will these changes affect ecosystem values? How do changes in the shape, pattern, and arrangement of forest parcels modify flows of energy, materials, and species? Answering these questions requires a synthesis of scientific knowledge about important ecosystem components and a means for integrating the knowledge in a format useful to resource managers.

Ecosystem management at any scale requires data. Currently the most common landscape analysis scale being used is at the watershed level. The question now is whether resource managers can take advantage of the large investments in more detailed geo-referenced data at the stand level in developing advanced analytical techniques for ecosystem management. A major obstacle is the procedural complexity of an integrated environment for the storage, processing, and display of mapped data used in forest simulation and landscape analysis. Currently, the linkage involves a litany of independent and specialized programs that severely limit rapid map displays and comparisons of future conditions for direct interpretation by forest managers. Communication between these systems and GIS data has been left to end-users and requires considerable programming knowledge of both systems' syntax, file types and formats, custom conversion programs, and operating procedures. The intimidating and confusing "mechanics" of the linkage has severely limited the effective use of GIS in forest growth modeling and landscape analysis. A seamless link between forest management programs and GIS data and spatial processing capabilities is needed.

This paper describes linkage of the FRAGSTATS landscape analysis and Forest Vegetation Simulator (FVS) programs to the ARC/INFO GIS. The seamless links provide a user interface that controls program specification, data handling, and output display.

Quantifying Landscape Structure

The developing field of landscape ecology serves as a strong conceptual and theoretical basis for understanding landscape structure, function, and change. These factors can be specifically defined as (Forman and Gordon 1986): structure is the spatial relationships among the distinctive ecosystems or "elements" present; function identifies the interactions among the spatial elements; and change is the alteration in the structure and function of the ecological mosaic over time. The ability to quantify landscape structure is prerequisite to the study of landscape function and change. For this reason, considerable emphasis has been placed on the development of landscape metrics. Many of the relationships can be expressed by indices derived through analysis of the shape, pattern, and arrangement of landscape elements spatially depicted as individual *patches* (for example, vegetation polygon), *classes* of related patches (for example, polygons of the same type/condition), and entire *landscape* sets (for example, all polygons).

Landscape analysis provides the techniques for the study of landscape patterns, the interactions among patches within a landscape mosaic, and how these patterns and interactions

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change over time. Geographic information systems (GIS) technology provides capabilities for computer encoding, storage, processing, and display of the spatial data. To date, the successful marriage of the science of landscape ecology and GIS technology has been sporadic. Much of the difficulty has arisen from the procedural complexity of linking the two systems in a common environment that scientists and managers can easily use.

Linking GIS and Landscape Analysis Capabilities

FRAGSTATS (McGarigal and Marks 1995) is an extensively used program that derives a comprehensive set of useful landscape metrics. The ARC/INFO system (ESRI 1992) is a powerful, workstation-level GIS that is widely used by natural resource agencies, organizations, and companies. Communication between the two programs, however, has been left to end-users and requires considerable programming knowledge of both systems' syntax, file types/formats, custom conversion programs, and operating system procedures. These intimidating and confusing "mechanics" of the linkage has severely limited the effective use of landscape analysis in natural resource planning and management.

A fully integrated link between ARC/INFO and FRAGSTATS requires a single user interface that controls program specifications, data transfers, and output display. A "seamless link" provides a user-friendly graphical menu consisting of scroll lists, toggles, and buttons to facilitate program specifications and automatically generate appropriate tables, charts, and maps for enhanced interpretation of the results. The *FRAGSTATS*ARC* interface develops such an environment by controlling: (1) the selection of maps, (2) direct access of the required ARC/INFO spatial and attribute tables, (3) selection of FRAGSTATS indices to be calculated and required program parameters, (4) program execution and generation of linked tables of FRAGSTATS results, (5) creation of meta-data files for control and tracking of multiple runs, and (6) display of results in a variety of tables, charts, and map plots.

The *FRAGSTATS*ARC* interface allows the user to select the ARC/INFO coverage(s) for input, landscape metrics for calculation, output forms, and processing environment control. These specifications are accomplished through a cascading menu bar with a "look-and-feel" similar to most Windows programs. The menu is organized into eight topics that follow the natural processing order:

- **File** File Management and Workspace specifications
- **Data** Input Data Selection, Data Preparation and Preprocessing, and direct attribute table access
- **Run** FRAGSTATS Program operation and run management tools
- **View** Thematic Mapping, Query & Display, Edge Contrast viewing, Attribute Listings, Tabular Attribute Reports, Graphing, and Pan/Zoom Tools
- **Tools** Numerous environment tools including Multiple Window Display, Slide Capture, Symbology Sets, direct access to Command Mode, and ARC/INFO Tool Picker Menus

- **Session** Environment Operating Preferences, Query Configuration, and User Profile Management
- **Help** FRAGSTATS Help Topics, About FRAGSTATS
- **Exit** Exit

The specifications entered via the pull-down menus and pop-up dialog boxes form an AML (Arc Macro Language) command file that controls data management and calculations. Figure 1 shows the *FRAGSTATS*ARC* pull-down menu (extreme upper left), the Pan/Zoom Tool Bar (extreme upper right), the FRAGSTATS Run dialog box (left side), and the plot of the selected coverage attribute (right side). The upper portion of the Run dialog box enables specification of Workspace and Input Data Selections. The Parameters section allows the user to easily modify program defaults via secondary pop-up menus or direct field entry. The lower portion of the Run dialog box sets the processing mode and indices for calculation. Completion of the specifications in the menu are accomplished by selecting, toggling, specifying, or accepting defaults of menu items, with contextual guidance at each step and little or no contact with the keyboard.

Upon program completion, the calculations are stored as a series of INFO tables linked to the specified coverage. Figure 2 shows a Thematic Map display of the edge contrast index. The top left menu is completed by the user to identify the coverage, attribute for display, and map type. The lower left box contains the automatically generated legend linking the six quantile (equal count) levels requested by the user to the default color palate (darker tones indicate less edge contrast). Users can easily switch to another color pallet by selecting one of several standard sets in the Shade Set scroll list, or designing their own. The number of display classes and thematic mapping method can be "toggled" and the display/legend is refreshed "on-the-fly." The display window (right side of fig. 2) can be automatically partitioned for simultaneous viewing (Multiple Windows Tool) of up to 12 different map displays of indices, mixing geographic areas, management scenarios, or summary graphs and tables.

Normally, FRAGSTATS output is a limited single formatted report that simply lists all of the indices for all of the polygons forming the input landscape coverage. Three tabular options are available in the *FRAGSTATS*ARC*: (1) listing of user-selected indices for on-screen review or export to other programs, (2) standard FRAGSTATS formatted report, and (3) custom tabular reports. The custom report generator in *FRAGSTATS*ARC* outputs formatted tables containing user-defined subheadings and statistics, such as the total Area and average Shape Index by Vegetative Species.

Graphical Interface and Common Environment

The *FRAGSTATS*ARC* interface provides a common processing environment and graphical interface for running FRAGSTATS within a workstation ARC/INFO configuration. User specifications for input maps, FRAGSTATS analysis parameters, and ARC/INFO output options are made by toggling options in a screen menu. The menu consists of a scroll list of maps within the user's active workspace, index level toggles (patch, class, and landscape), verification fields,
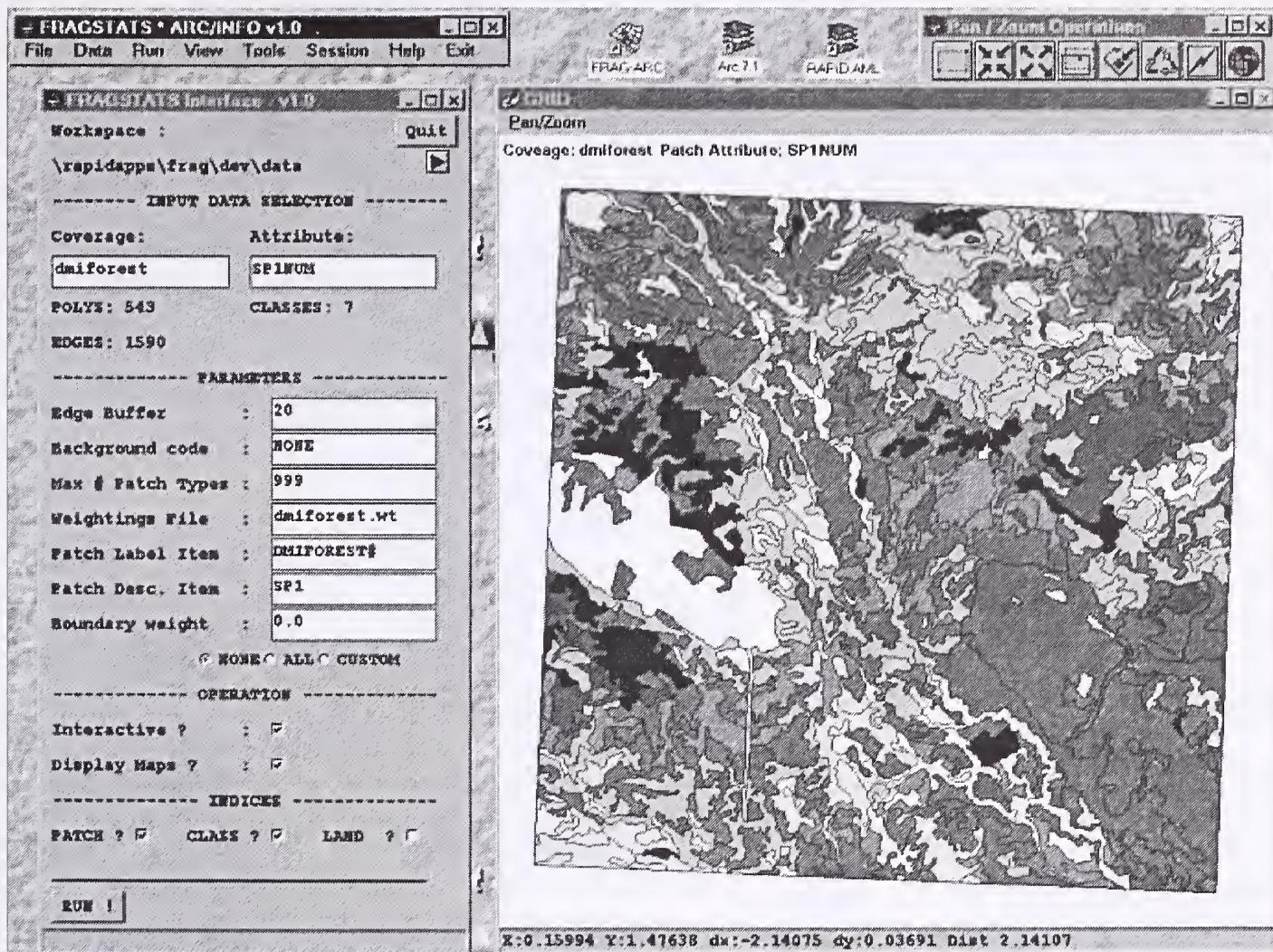
Figure 1—The FRAGSTATS*ARC interface. This figure illustrates the main pull-down menu along with the primary interface menu for starting a FRAGSTATS run.

and display option toggles. During execution, the specifications automatically access the selected maps in ARC/INFO for FRAGSTATS computation, calculates the specified indices, stores the results to a fully structured ARC/INFO coverage (complete with related INFO tables), and generates the desired output products.

*FRAGSTATS*ARC* enables scientists and managers to interact with both FRAGSTATS and ARC/INFO without extensive procedural knowledge of either system. It "seamlessly" integrates both systems in a friendly environment allowing users to directly concentrate on ecological planning and management implications, without the distracting "mechanics" of program control and output generation. Within the program, each vegetation polygon (in other words, patch) is identified by a Patch ID followed by a two-column listing of the calculated metrics. The patch ID serves as the link between the tabular listing (attribute data) and the map displays of the polygons (spatial data) in the construction of fully structured ARC/INFO tables containing the landscape indices.

Users of earlier versions of FRAGSTATS were required to preprocess ARC/INFO vector coverages, such as DISSOLVE polygon boundaries, BUFFER edges, and UNION buffer

and dissolve boundaries, prior to file export. Program interaction was restricted to command mode operation of AML macros with arguments, without the flexibility of a GUI interface. The output was restricted to formatted output files, which was difficult to integrate with other programs, such as spreadsheets and data bases, with no return linkages to ARC/INFO for map display of the calculated indices or further GIS modeling. The major features provided in *FRAGSTATS*ARC* beyond the older versions of FRAGSTATS include:

- Seamless link to spatial data (no import/export of data tables)
- GUI interface for input specification and program execution
- Individual index selection as well as entire patch, class, or landscape groups
- Meta-data file scheme for workspace organization and multiple-run tracking
- Improved performance (1.5 hr to 20 sec for test run of approximately 2,000 polygons)
- Data base file output as well as standard and custom formatted reports
- Support of ARC/INFO libraries as well as single coverages
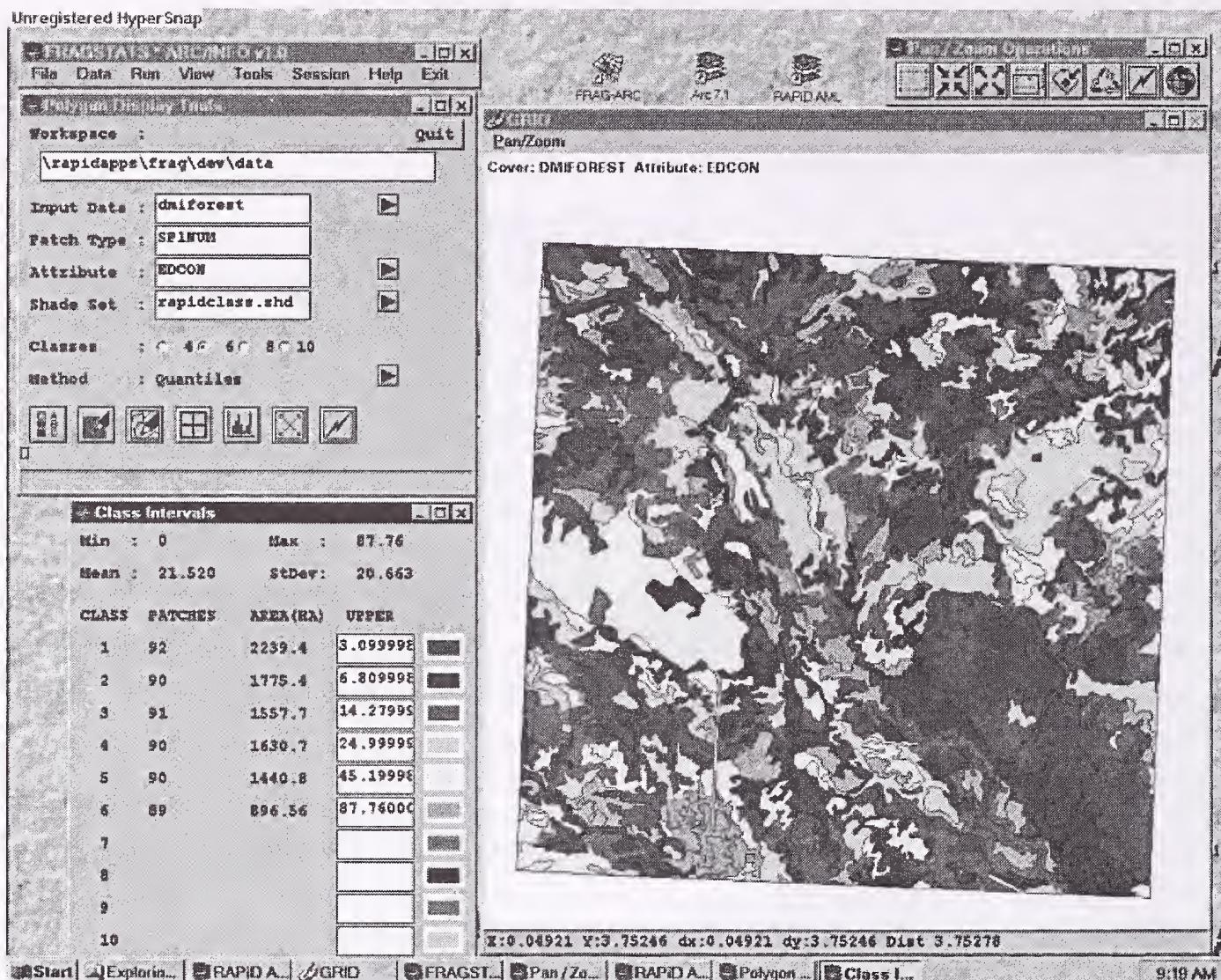
Figure 2—The Thematic Mapping tools allow the user to seamlessly create thematic displays of FRAGSTATS output PATCH indices with the aid of quantitative classification tools.

- Client/server batch processing as well as interactive modes
- GUI interface for results query and display

The *FRAGSTATS*ARC Query and Display* module contains a graphical interface for constructing and automatically displaying data base selections, such as selecting all "aspen (Aw) vegetation parcels > 15.00 hectares with a shape index > 2.00," then thematically mapping the relative Edge Contrast Indices for the selected parcels. The module provides several display options, including automated thematic mapping, generation of frequency plots, and multi-window screen partitioning.

Figure 3 depicts the query and thematic plot described above with the darkest polygons locating the small, irregular aspen stands in the project area. The Query menu on the left was activated simply by selecting Query & Display item from the Main Menu pull-down. By default, the current FRAGSTATS table is identified, or the user can select a new one from a pop-up scroll list of available tables. The Query Ladder tracks the sequence of queries entered by the user, using the Feature Selection buttons. For example, the second step in the ladder (RESELECT > SP1 EQ 'Aw') selects the Aspen polygons (Aw) from all species polygons (SP1)

based on the logical expression of attribute equivalence (EQ). Spatial query (for example, as all locations within 0.25 miles) and topological query (for example, adjacent to) are available. Users can move up and down in the query ladder as they investigate different assumptions, then save their spatial reasoning (AML macro) to a file for later use. The Display Tools in the extreme upper right portion of figure 3 allows users to quickly modify map displays and generate reports of query results.

Simulating Forest Conditions and Management Alternatives

Landscape analysis provides a useful set of metrics for describing the shape, pattern, and arrangement of landscape elements. Historical maps and imagery provide mapped data describing prior and existing landscape structure, however, questions about resource sustainability and utilization often require future forest conditions to be described in the same level of detail. Forest growth simulation provides realistic forecasting tools coupling currently available resource information and the latest scientific results.
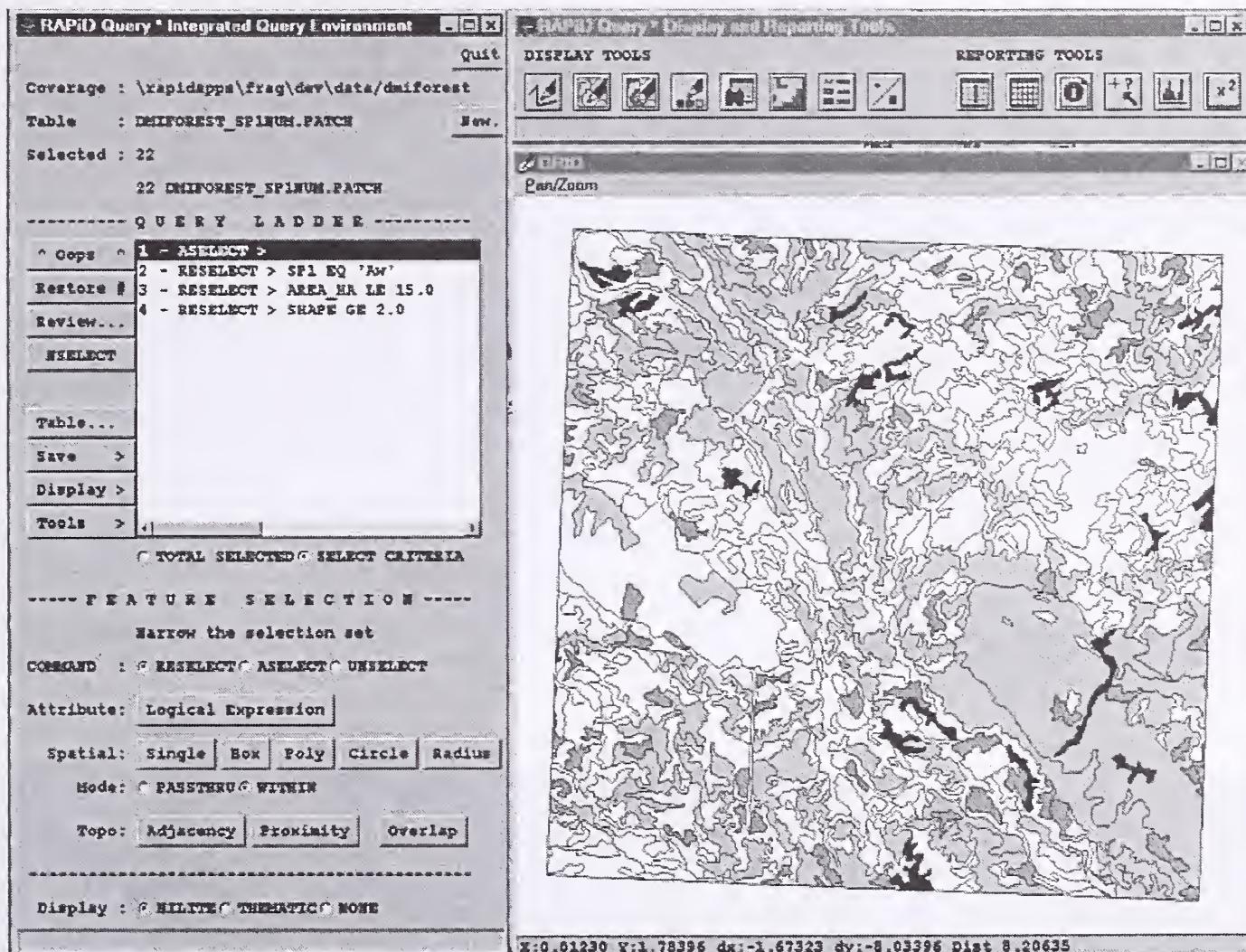
Figure 3—The Query and Display tools provide a comprehensive query environment for interrogating FRAGSTATS output PATCH indices using a logic tracking approach to aid the user (the Query Ladder).

Forestry organizations are beginning to link stand exam data to their geographic information systems and populating the data bases with stand level indices, such as species composition, canopy closure, and vegetative structural stage. These indices are used within the GIS to define forest health in management terms, such as fire hazard, insect hazards, hiding cover, and vegetative structural stage diversity. However, forest analysts encounter two main obstacles limiting their ability to take advantage of the existing data and the new tools that are at their disposal: (1) they are limited to populating their GIS data base with only those attributes currently defined by their stand exam/inventory systems, and (2) they are limited by the procedural complexity of linking data to the tools.

Linking GIS and Forest Growth Simulation

The Forest Vegetation Simulator (FVS) is a distance-independent, individual-tree, forest growth model used extensively by the U.S. Forest Service. At the core of the FVS system is an individual tree, distant-independent, growth and yield model. Tightly linked to the growth model are a variety of modules representing other important ecosystem components and analytic tools for simulating management activities. FVS is designed to make consistent forecasts across a broad range of planning scales and can represent forest ecosystems of widely differing species and structural mixes. The family of FVS programs are calibrated to specific geographic regions allowing forest managers and scientists to access a common analytical tool for their unique conditions.

The original FVS growth model has its structural roots in the Stand Prognosis Model (Stage 1973). The basic model contains modules for growing trees, predicting mortality, establishing regeneration, predicting nontree vegetation development, performing management activities, calculating tree volumes, and producing reports on stand structure, species composition, and forest products (Wykoff and others 1982). The Event Monitor module allows dynamic scheduling of management activities during a simulation based on stand conditions specified by the user. The flexibility in defining silvicultural prescriptions makes FVS a robust tool for comparing management alternatives.

Model input includes (1) "treelist" records for each forest stand, (2) regional-specific data translator, (3) geographic variant growth functions, and (4) keywords which act as

operating instructions. The treelist stores individual tree diameter, height, species, crown ratio, crown diameter, tree volume, number of live, dead, or cut trees per acre, and other tree attribute information updated each projection cycle. The data translator converts region-specific stand exam data to a standard FVS format. Growth function variants define parameters for growth functions for a variety of geographic locations. The keyword files contain simulation instructions and output/post-processing desired. The recently developed Suppose module provides Windows-type access to the simulation model for packaging the FVS data sets, variant, and keywords into a run-stream for both batch and interactive processing.

Model output consists of (1) individual tree metrics for projection cycles, (2) stand metrics for projection cycles, (3) information on understory, and (4) data files for auxiliary programs. The FVS treelist output report lists information on every tree record in the original input file, including snags and new trees brought into the simulation through the regeneration module. The post-processor incorporates the simulation output into other algorithms for generating structural stage, stand and stock tables, wildlife habitat relationship, habitat stages, snag tables, elk hiding cover, and variety of other information.

*FVS*ARC* provides a seamless link between FVS and ARC/INFO that controls program specifications, data transfers, and output display. It provides a user-friendly graphical menu consisting of scroll lists, toggles, and buttons to facilitate program specifications, control program execution, and automatically generate appropriate tables, charts, and maps for enhanced interpretation of the results. Specifically, FVS*ARC controls the (1) selection maps, (2) transfer of maps within ARC/INFO, (3) selection of FVS indices and control of program execution, (4) transfer of FVS results to ARC/INFO, (5) creation of meta-data files for control of multiple runs, and (6) display of results in a variety of tables, custom reports, charts, movies, and map displays.

User interaction with *FVS*ARC* is similar to that described for the *FRAGSTATS*ARC* program. The left portion of figure 4 shows the main FVS*ARC menu which is divided into three sections. In the Data Set Definition section the user specifies the workspace, coverage, and attribute tables for the area of interest. The plot in the right portion of the figure is a map display of the selected coverage. The FVS

Figure 4—The FVS*ARC interface. This figure illustrates the main menu along with a display of the specified ARC/INFO coverage.

Parameters section allows the user to select and edit the keyword lists forming the run-stream for the desired simulation. The Action Button section provides access to the submittal system, entry to the post-processing system, execution of the variant simulation, and query and display of the results. The right portion of the figure shows a plot of all of the stand boundaries in the selected area. The Pan/Zoom Operations toolbar allows the user to interact with any map displayed.

Figure 5 shows the results of a query and display of an FVS simulation. The *FVS*ARC* system was used to generate a 50 year simulation of forest growth and yield for nearly 1,600 forest stands, then the query and display tools were used to identify a subset of commercial stands with roads passing through them. The steps involved in generating the simulation involved activating the main *FVS*ARC* menu and selecting the coverage, defining the keyword list, specifying program parameters, and accessing the submittal and post-processing modules. The "Query by Attribute" pop-up in the left portion of the figure shows the "point-and-click" highlights of scroll list items used to select forest stands with d.b.h. greater than 8 inches. The plot in the right portion of the figure shows a map display of all the stands meeting this criteria (time = initial state), color-coded by species. Results of the complete analysis identified only 58 of the 1,541 stands (polygons) used in the simulation that met all three criteria (d.b.h. > 8 inches; BA > 150 sq ft per acre; with existing road). Interactive specification for the query and display of the ARC/INFO tables containing the FVS simulation results took less than 3 minutes.

As with FRAGSTATS, users of earlier versions of FVS were required to "manually" effect all data handling and processing control through a series of disjoint programs and steps. Program interaction was restricted to command line operation without the flexibility and ease of a GUI interface. The standard output was fixed formatted files that had to be "parsed" by post-processing programs for integration with other programs and GIS. The major features provided in the FVS*ARC interface include:

- Seamless link to spatial data
- GUI interface for input and execution
- GUI interface for query and display of results
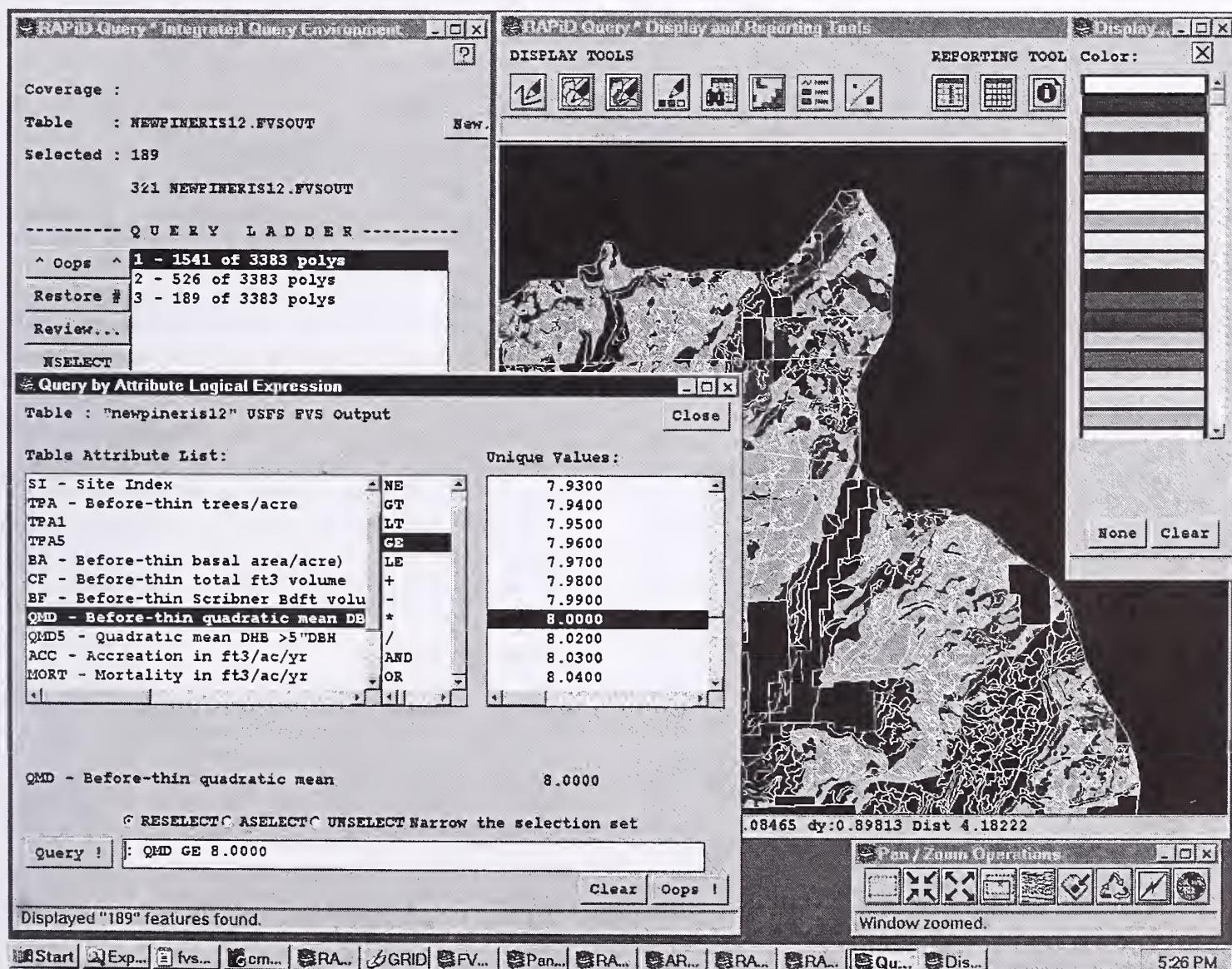
Figure 5—The Query and Display tools can be used for generating custom reports and maps of FVS output.

- Keyword file management and editing
- Data base file output as well as formatted reports
- Support of ARC/INFO library as well as single coverages
- Client/server batch processing

The *FVS*ARC* and *FRAGSTATS*ARC* systems are fully compatible. Users can FVS to simulate various management alternatives for an area, calculate landscape indices for any time step, then view the results of future forest conditions and landscape structure characteristics. Although the two systems appear similar to users, they use different approaches in the linking to the GIS. The *FVS*ARC* link is the more commonly used technique for linking existing models. The link to the data is made through a common identification number for each forest stand (polygon). Intermediary files are used for data transfer between the program and the GIS. Although relatively easy to construct, this approach is relatively inefficient and fails to take advantage of the spatial analysis capabilities in the GIS. It uses the GIS for data input (data preprocessing) and output (map displays), but retains the existing program for "thruput."

The *FRAGSTATS*ARC* link, on the other hand, fully incorporates the FRAGSTATS program into the GIS by restructuring and expressing it as an ARC/INFO AML (Arc Macro Language). This approach has three main advantages, efficiency, performance, and extended capabilities. By coding the program in the GIS, import/export of external files is no longer necessary as all operations access a common data base. Performance is improved by substituting table-based operations for many of the iterative operations based on cycling through the entire set of polygons. By converting from a traditional programming language to a fully integrated GIS implementation, a robust set of spatial operators becomes available. For example, the calculation of distance becomes a single line call to optimized routine within the GIS, replacing numerous lines of embedded and linked user-derived code. The extension from simple Euclidean distance to effective distance respecting maps of absolute and relative barriers involves the addition of a few parameters in the single line call.

The decision between an externally linked or a fully integrated connection depends on the program's spatial character and complexity. In the case of the *FVS*ARC* application, the program is an extremely complex "independent tree" model with minimal spatial considerations—an ideal candidate for external linkage. On the other hand, the *FRAGSTATS*ARC* application involves relatively simple code and, by its very nature, is extremely spatially dependent—an ideal candidate for full integration. The authors have experience in linking a wide range of models, from water billing systems, wildfire propagation, ecosystem dynamics, to atmospheric dispersion models, and each link to GIS had to be matched to the existing code and aspirations of the client.

Future Efforts

An extension project for *FRAGSTATS*ARC* is planned to provide additional landscape structure indices and new capabilities for generating custom queries and rapid comparison of FRAGSTATS output. It will enable a user to launch several FRAGSTATS analyses, then generate comparative statistics and output these results as a variety of tables, charts, and map displays. For example, a user might compare three harvesting scenarios for an area to determine which indices significantly change and output the results as a map of affected landscape units. In addition, support to the PC versions of FRAGSTATS and desktop mapping systems, such as ArcView and MapInfo, as well as a custom ESRI MapObjects interface (GIS platform independent software) will be considered. Several new indices and modifications, such as the lacunarity index and various other texture metrics, will be incorporated within the *FRAGSTATS*ARC Extensions* environment.

Several extensions to the *FVS*ARC* system are anticipated to include links to the comparative analysis module, direct access to the GUI submittal system, and a GUI interface to the post-processing system. The potential for providing spatial analysis functionality to variant calculations (for example, slope/aspect, proximity, and so forth) will be investigated. Of particular importance is the visual representation of the forest simulations. These renderings will be generated from the FVS treelist output by executing the 3-D visualization system, *Virtual Forest,* under development by the authors. The visualization created by *Virtual Forest* will be linked spatially to the ARC/INFO data base and available for viewing simply by specifying an area and time step.

Conclusions

The quantification of landscape structure provides a new set of tools for understanding the complex spatial patterns and interactions among landscape features. Forest simulation provides realistic forecasting tools of future forest conditions based on currently available resource information and proposed management actions. Both promise new approaches for the visualization, formulation, and solving of real-world problems. However, the tools must be integrated into a system designed for use by resource managers, scientists, and other end-users with minimal procedural knowledge of the programs involved. The *FRAGSTATS*ARC* and *FVS*ARC* systems achieve this integration by seamlessly linking the ARC/INFO GIS to the FRAGSTATS and FVS programs within a common graphical user environment for storage, processing, and displaying of mapped data used in landscape analysis and forest growth modeling.

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Acknowledgments and Further Information_____

Guidelines for Sensitivity Analysis of FVS

David A. Hamilton, Jr.

Abstract—Sensitivity analysis is an important component of the model development process that is frequently either ignored or, if considered at all, done incorrectly. Sensitivity analyses may be used to identify model components or relationships within components that should have high priority for future research efforts. They may identify the level of inventory precision and accuracy required when collecting information needed to run a model. They may increase understanding of model performance and thus play a role in the model validation/verification process. Examples of each of these uses, drawn from the sensitivity analysis of the Forest Vegetation Simulator (FVS), are discussed.

A sensitivity analysis is an important component of the model development process that unfortunately is frequently either ignored or done incorrectly. Innis (1979) defined sensitivity analysis as a "systematic search for those model entities to which the model is most sensitive." A sensitivity analysis may provide insight as to how the model can be expected to perform both as currently configured and if modified to better describe some key relationship. This may not mean to model developers the same thing it does to model users. Looking at specific uses of sensitivity analysis may help clarify these differences.

Frequently, sensitivity analyses are designed to evaluate sensitivity to changes in parameter values and sensitivity to changes in functional relationships in the model. In this context they help determine how precise parameter estimates need to be and the adequacy of the functional relationships making up the model. When small changes in a parameter or component model lead to large changes in model output, that parameter or component model should be considered a strong candidate for further research effort to improve the predictive or explanatory capabilities of the model. Conversely, when changes in a parameter or component model have a minor impact on model output, little justification exists for expending further research effort. This use of sensitivity analysis illustrates a paradox described by Swartzman (1979). The paradox lies in the fact that the analysis and resulting inferences are based on the assumption that the model is true while the fact that the analysis may suggest that future research is needed implies that at least certain components of the model may not be true. Thus, even when sensitivity analysis suggests low priority for future research, validity of the basic relationships that make up the model can only be verified through additional research. The importance of this use for model developers is obvious. It provides users with information

needed to evaluate the impact of model changes on current applications of the model.

Users have a strong interest in analyses of the sensitivity of model output to changes in the value of independent variables. Such analysis helps managers and planners in designing inventories that provide estimates of independent variables needed to run the model, with an emphasis on those variables model output is most sensitive to. This provides information on how much sampling accuracy is needed for each variable and on the amount of measurement precision required for each variable. For example, does diameter at breast height (d.b.h.) need to be measured to the nearest 0.1 inch, to the nearest inch, or perhaps to the nearest 2 inches?

A sensitivity analysis may increase understanding of model performance and be used to identify limits of applicability of a model. Limits of applicability are defined by the range of applicable values of the independent variables and by the accuracy of model predictions throughout this range. This helps determine if the model is useful for an intended application, helps interpret the results of a model run in a specific environment (Innis 1979), and identifies conditions for which model performance does not match the modeler's understanding of biological reality. Unexpectedly large or small sensitivities may suggest the possibility of coding or logic errors in the model, thus contributing to model validation/verification.

Methods

"Parameter perturbation" is the sensitivity analysis methodology I use in this paper. In its simplest form, this method involves changing a parameter from its estimated value, running the model, and observing the resulting changes in model output. The advantage of this approach is that it is easy to apply. The primary disadvantage is that if any of the relationships are nonlinear or if interactions exist between parameters, inferences drawn from the sensitivity analysis may be in error.

To carry out a sensitivity analysis in the presence of interactions, more than a single parameter must be perturbed in a single run. Unfortunately, this modification may lead to a further problem. In a large complex system there likely will be too many parameters to permit making a model run for each possible combination of parameter values. Steinhorst and others (1978) suggested using the methodology of fractional factorial experimental design to reduce the number of model runs needed to make valid inferences about parameters and interactions.

This paper looks at two phases of the sensitivity analysis of FVS, sensitivity to changes in functional relationships in the model and sensitivity to variation in input values. The first phase is further divided into an examination of sensitivity to changes in overall levels of component models and an examination of sensitivity to changes in component model levels in specified subsets of the d.b.h. distribution.

Sensitivity to changes in overall levels of component models is examined by treating each of the four primary component models (basal area increment, height increment, mortality, and crown ratio) as the "parameter" to be perturbed. Component models are perturbed by applying one of the following FVS multipliers to the component model: BAIMULT (large tree basal area increment multiplier), MORTMULT (mortality multiplier), HTGMULT (large tree height increment multiplier), CRNMULT (crown ratio increment multiplier), REGDMULT (small tree diameter increment multiplier), or REGHMULT (small tree height increment multiplier). The appropriate levels of perturbation must be determined. Possibilities might include plus or minus one standard deviation, plus or minus some fixed percent, or setting perturbations at extremes of the range of possible values. The general guidelines offered in setting level of perturbation suggest that they should remain within known or hypothesized values (they should be realistic) and that they should be selected to permit a thorough exploration of the response surface. However, the determination of those parameters or model components that the model is most sensitive to identifies those relationships within the model needing further research attention. Thus, in design of the analysis (particularly in selecting size of perturbations) it is better to err in the direction of finding too many rather than too few parameters (or model components) that model output is sensitive to (Innis 1979).

A second argument that favors the selection of large perturbations is related to the validation/verification objective of sensitivity analyses. Such selection permits examination of model performance at extreme values of parameters, resulting in a definition of the limits within which models may be extrapolated. To evaluate sensitivity to changes in overall level of component models, I applied perturbations of plus or minus 10, plus or minus 50, and plus or minus 70 percent to each of the component models. This was accomplished by using multipliers of 0.3, 0.5, 0.9, 1.0, 1.1, 1.5, and 1.7. The multiplier 1.0 represents the unperturbed condition.

A full replication of the analysis would require making a model run for each of the 7^4 possible combinations of four model components perturbed with each of these seven multipliers. This may be treated as a 7^4 factorial design in which each of the component models is considered to be a treatment, and each of the seven levels of perturbation are considered to be treatment levels. A $1/7$ replication of the full experimental design was used to reduce the required number of runs from 2,401 to 343. The combinations of the four model components that make up the $1/7$ replicate were selected by methods described by Cochran and Cox (1957). Each of the main effects are unconfounded with each other and with two-way interactions in the resulting design, but some of the two-way interactions are confounded with each other. This results in some unavoidable loss of information on two-way interactions.

The second phase of the examination of sensitivity to changes in functional relationships is carried out by treating model components in specified subsets of the d.b.h. distribution as the "parameters" to be perturbed. By systematically increasing or decreasing rates of change in the tails and central portion of the d.b.h. distribution, information can be obtained concerning the sensitivity of model output to variation in functional relationships in these portions of the

distribution. This phase of the analysis may be used to rank the relative importance of changes that occur early, in the middle of, and late in the stand development process.

This phase of the analysis was carried out by dividing the d.b.h. distribution into three segments, less than 3 inches, 3 to 10 inches, and greater than 10 inches. Each of the four model components was perturbed plus or minus 50 percent in each segment of the d.b.h. distribution. This was implemented with multipliers of 0.5, 1.0, and 1.5. The analysis can be carried out as a 3^{12} factorial design. The full experimental design would require a run of FVS for each of the 531,441 possible combinations of 12 treatments (three segments of the d.b.h. distribution for each of four component models) and three treatment levels (the multipliers 0.5, 1.0, and 1.5). A more manageable analysis is defined by a $1/3^7$ fractional replication of the design, which requires 243 model runs. This design required seven defining contrasts (Cochran and Cox 1957) that did not result in any main effects being confounded with each other or with any two-way interactions and that minimized the confounding of two-way interactions.

Sensitivity to variation in input values was divided into two parts; an examination of the impact of measurement precision on model sensitivity, and an examination of the impact of measurement accuracy on model sensitivity. For this part of the analysis, input variables are the "parameters" to be perturbed. In this study, measurement precision refers to the measurement scale used to measure each variable. Alternative measurement scales are the levels of perturbation. Variables and measurement scales included in the evaluation were crown ratio measured to the nearest 10 percent (the current standard), the nearest 20 percent, or to the nearest third of total stem height; d.b.h. measured to the nearest 0.1 inch (current standard), to the nearest inch, or to the nearest 2 inches; and height measured to the nearest foot (current standard), to the nearest 2 feet, or to the nearest 5 feet. Sensitivity of model output to variation in measurement accuracy was evaluated by perturbing the value of input variables by plus or minus 10 percent.

Each of the two parts may be analyzed with a 3^3 factorial design in which the treatments are the three input variables and the treatment levels are the three levels of perturbation. This analysis requires only 27 model runs, so there is no need to use fractional replication. Perturbation of the input variables was accomplished by creating 27 tree record input files. Each consists of one of the 27 possible combinations of true or perturbed values for the three variables being evaluated. For example, one run in the analysis of sensitivity to variation in measurement precision would be made with an input data set in which crown ratio is measured to the nearest 10 percent, d.b.h. measured to the nearest 2 inches, and height measured to the nearest 2 feet. The next run might consist of crown ratio measured to the nearest 20 percent, d.b.h. measured to the nearest 0.1 inch, and height measured to the nearest 5 feet.

One must determine which measures of model response or output should be used to evaluate model sensitivity. The selected measures are called sensitivity indicators. Innis (1979) suggests the following criteria for selecting indicators: they should demonstrate that the objectives of the model are being satisfied and that each component of the model is performing properly; they should be based on the modeler's intuition or accumulated knowledge about how

the system works; and they should include no more than 10 measures of output. For the FVS study, sensitivity indicators were total cubic volume (VOL), trees per acre (T/A), quadratic mean diameter (QMD), top height (THT), stand basal area (BA), and diameter distribution. Each measure was evaluated over a range of stand projection lengths (40 to 200 years). Most examples in this paper use total cubic volume and trees per acre evaluated at ages 100 and 200 years.

Two stands were included in the analysis in order to examine interactions between site productivity and sensitivity. The first was a relatively low productivity site on an *Abies grandis/Clintonia uniflora* habitat type on the Lolo National Forest, MT. The second was a high productivity site on a *Tsuga heterophylla/Clintonia uniflora* habitat type on the Clearwater National Forest, ID. The regeneration establishment extension of FVS was used to generate the stands to be analyzed.

Evaluation of the sensitivity of the model to variation in input variables required that each model run begin with an inventory of an existing stand rather than with a stand generated by the regeneration establishment model. The stand used in the simulations is a 60 year old stand on a *Tsuga heterophylla/Clintonia uniflora* habitat type on the Clearwater National Forest.

If interactions between site conditions and sensitivity exist, they may not be detected by these examples. The relatively low productivity and relatively high productivity sites were selected in an attempt to explore whether such interactions exist. Future research should thoroughly evaluate differences that may exist in sensitivities across the almost infinite array of possible stand conditions.

Results

Because FVS is primarily a deterministic model, there is essentially no element of random error contained in the values of sensitivity indicators obtained for each run of the program. Thus, the results of the analyses of variance of the designs described above cannot be interpreted as valid statistical tests with reported levels of significance. Instead, the results provide an objective way to evaluate the relative sensitivity of the model to variation in the levels or shape of each component model or to variation in input values. The practical significance of any observed level of sensitivity will depend on the context within which the model developer or model user makes the evaluation.

The most obvious and consistent result of the analysis of the sensitivity of FVS to variation in overall levels of component models (tables 1 and 2) was that variation in the rate of change in crown ratio had little impact on any of the sensitivity indicators. This held true for both stands and for all stand ages evaluated (40 to 200 years). This doesn't say that crown ratio is not an important variable in the component models. Rather, it implies that because crown ratio changes so slowly over time, variation in the rate of change in crown ratio has little effect on model output.

For most of the other component models, sensitivity increases as size of the perturbation increases. Selection of the sensitivity indicator has a strong impact on the pattern of observed sensitivity. In other words, it is important to identify accurately what it is that you really want the model to predict well. If trees per acre is the criterion of interest, mortality is the model component that displays the highest

Table 1—Percentage change in sensitivity indicators for a high productivity stand when component models are perturbed ±70 percent, ±50 percent, and ±10 percent.

	100 years						200 years					
	−70	−50	−10	10	50	70	−70	−50	−10	10	50	70
						-Percent-						
Basal area increment												
T/A	14	17	5	−4	−20	−27	41	33	7	−6	−24	−31
VOL	−62	−40	−6	5	17	21	−63	−39	−5	6	17	22
QMD	−54	−35	−6	5	25	34	−54	−33	−5	6	24	33
THT	25	5	1	0	−3	−3	6	−1	0	0	−2	−3
BA	−72	−45	−6	6	19	22	−67	−38	−5	5	15	17
Height increment												
T/A	0	1	2	−2	−7	−9	4	3	2	−3	−7	−9
VOL	−73	−49	−9	11	42	57	−65	−43	−7	9	31	42
QMD	−21	−11	−2	3	7	10	−6	−4	−1	2	5	7
THT	−58	−38	−8	7	28	40	−59	−38	−6	7	25	33
BA	−33	−15	−2	2	5	6	−11	−5	−1	1	2	3
Mortality												
T/A	207	110	14	−11	−41	−50	385	157	16	−13	−44	−54
VOL	56	34	5	−5	−20	−25	87	48	7	−7	−26	−33
QMD	−21	−11	−2	3	7	10	−36	−22	−3	3	13	17
THT	1	1	0	0	−1	−1	3	2	0	−1	−5	−8
BA	63	38	6	−5	−21	−27	94	51	7	−7	−27	−34
Crown ratio												
T/A	2	2	0	0	1	1	0	1	0	0	0	1
VOL	−2	−2	−1	0	0	−1	−1	−2	−1	0	0	0
QMD	0	0	0	0	0	1	1	0	0	1	0	1
THT	0	0	0	0	0	0	0	−1	0	0	0	0
BA	1	1	0	1	1	1	0	1	0	0	0	0

Table 2—Percentage change in sensitivity indicators for a low productivity stand when component models are perturbed ±70 percent, ±50 percent, and ±10 percent.

	100 years						200 years					
	−70	−50	−10	10	50	70	−70	−50	−10	10	50	70
	- -Percent -												
Basal area increment												
T/A	−33	−18	−2	1	−2	−5	−38	−15	0	−1	−12	−17
VOL	−73	−55	−10	9	36	45	−75	−53	−8	6	22	27
QMD	−56	−37	−6	5	24	31	−51	−31	−5	4	20	27
THT	71	18	2	−1	−5	−7	57	9	1	0	−3	−3
BA	−86	−66	−12	11	47	59	−86	−60	−9	8	28	33
Height increment												
T/A	−30	−19	−3	3	11	14	−28	−15	−2	2	7	8
VOL	−80	−55	−10	10	43	61	−66	−43	−7	7	29	39
QMD	−18	−6	0	0	0	1	5	2	0	−1	−2	−1
THT	−64	−41	−7	7	29	35	−57	−36	−6	5	24	28
BA	−51	−26	−2	3	11	14	−19	−9	−1	1	3	4
Mortality												
T/A	77	48	7	−7	−27	−34	163	86	11	−9	−36	−44
VOL	24	16	3	−3	−12	−16	54	33	5	−5	−20	−26
QMD	−14	−10	−2	2	8	11	−20	−13	−2	2	9	12
THT	−1	−1	0	0	−1	−1	−2	−1	0	1	2	2
BA	28	18	3	−3	−13	−18	59	36	5	−5	−21	−27
Crown ratio												
T/A	−2	−2	−1	0	−1	−2	0	−1	−1	1	1	1
VOL	−2	−2	0	−1	−1	−2	−2	−2	0	0	0	−1
QMD	0	−1	0	0	1	1	0	0	0	0	1	1
THT	0	−1	0	0	1	1	1	−1	0	0	0	1
BA	−2	−2	0	0	−1	−1	0	0	0	0	0	0

sensitivity. If total cubic volume is the criterion of interest, height increment is the most sensitive component, and basal area increment displays a somewhat lower degree of sensitivity. Mortality has reduced sensitivity for total cubic volume.

Differences in sensitivity between the high productivity stand and the low productivity stand are minor. With the exception of sensitivity to change in the mortality model, at age 100 sensitivities are slightly higher for the low productivity stand, and at age 200 there is little consistent difference. Sensitivity to changes in the mortality model is greater on the high productivity stand. This is most apparent when trees per acre is the sensitivity indicator.

With the exception of sensitivity to changes in mortality rates, most sensitivities are smaller at age 200 than they are at age 100. For all sensitivity indicators except trees per acre, perturbation of component models throughout a simulation does not result in increasing percentage differences in sensitivity indicators. One inference that may be drawn from this result is that the interrelationships between component models appear to be functioning as our understanding of the underlying growth processes suggest they should function. For example, faster basal area increment leads to higher densities, which results in higher levels of mortality and lower basal area increments, which then leads to lower basal areas. This scenario approximates our understanding of the growth processes controlling stand development. Thus, as long as perturbations remain "reasonable," the model components appear in fact to reproduce expected patterns of stand development.

Results of the analysis of sensitivity to changes in component model levels in specified subsets of the d.b.h. distribution (tables 3 and 4) were generally similar to those just discussed. The most striking new result was the general lack of sensitivity at age 200 to anything that occurs in the less than 3 inch diameter class. The only exception is mortality when trees per acre is the criterion of interest. Results for age 100 are similar except that changes in height increment in the less than 3 inch class results in moderate sensitivity when indicators total cubic volume or stand basal area are used for evaluation. These results support the inference that the interrelationships between component models have been modeled in such a way that as long as perturbations remain "reasonable," model components appear to reproduce expected patterns of stand development.

The final set of results deals with sensitivity of model output to variation in accuracy and precision of input variables. The accuracy assessment (table 5) shows the strongest sensitivity is associated with variation in d.b.h. Because basal area increment is the principal large tree model component, this is not an unexpected result. Sensitivity was perhaps slightly reduced for a 200 year projection (versus 100 years). With few exceptions, a 10 percent bias in the value of input variables resulted in at most a 2 to 5 percent change in sensitivity indicators. Results of the analysis of sensitivity to variation in measurement precision of input variables (table 6) show little sensitivity (nothing greater than 3 percent). When comparing these results with those obtained in the first example (analysis of sensitivity to changes in functional relationships), it must be remembered

Table 3—Percentage change in sensitivity indicators for a high productivity stand when component models are perturbed ±50 percent in specified ranges of the d.b.h. distribution.

	100 years						200 years					
	<3 inches		3-10 inches		>10 inches		<3 inches		3-10 inches		>10 inches	
	−50	50	−50	50	−50	50	−50	50	−50	50	−50	50
	-Percent-											
	Basal area increment											
T/A	2	−3	12	−7	6	−6	3	−4	9	−3	16	−13
VOL	−2	0	−21	5	−23	15	−1	1	−3	0	−38	18
QMD	−10	5	−17	7	−12	9	−5	3	−6	3	−23	16
THT	9	−5	5	−2	−8	3	4	−3	3	−2	−8	2
BA	−15	6	−20	6	−15	8	−5	3	−5	2	−31	12
	Height increment											
T/A	4	−9	−1	−1	0	0	5	−6	−1	−1	−1	0
VOL	−24	11	−13	14	−16	14	−10	7	−8	7	−24	18
QMD	−11	7	1	−2	0	0	−6	4	1	−1	1	0
THT	−4	3	−13	12	−20	18	−2	1	−8	8	−26	20
BA	−20	5	2	−1	0	0	−6	3	1	−1	1	−1
	Mortality											
T/A	57	−19	28	−16	6	−4	39	−12	49	−21	29	−13
VOL	2	−2	9	−5	21	−15	2	−1	3	−4	41	−23
QMD	−18	9	−8	6	4	−3	−12	5	−16	10	2	−3
THT	−1	1	0	−1	2	−3	−1	0	0	−1	3	−5
BA	5	−3	12	−7	17	−12	4	−2	6	−4	39	−20
	Crown ratio											
T/A	0	0	0	0	0	0	0	0	0	0	0	0
VOL	0	0	0	0	0	0	1	0	0	0	0	0
QMD	0	0	0	0	0	0	0	0	0	0	0	0
THT	0	0	0	0	0	0	0	0	0	0	0	0
BA	0	0	0	0	0	0	0	0	0	0	0	0

Table 4—Percentage change in sensitivity indicators for a low productivity stand when component models are perturbed ±50 percent in specified ranges of the d.b.h. distribution.

	100 years						200 years					
	<3 inches		3-10 inches		>10 inches		<3 inches		3-10 inches		>10 inches	
	−50	50	−50	50	−50	50	−50	50	−50	50	−50	50
	-Percent-											
	Basal area increment											
T/A	−16	9	−2	−4	2	−3	−15	5	−3	−3	0	−9
VOL	−18	7	−34	11	−20	18	−10	2	−12	2	−39	23
QMD	−12	4	−20	10	−9	7	−4	1	−8	4	−19	15
THT	16	−7	7	−4	−8	1	9	−4	7	−3	−7	1
BA	−33	17	−36	14	−15	11	−19	6	−18	5	−35	18
	Height increment											
T/A	−21	12	0	1	0	0	−17	7	1	1	0	0
VOL	−35	17	−18	19	−12	10	−14	5	−9	11	−19	15
QMD	−10	2	2	−1	0	0	0	−1	2	1	1	−1
THT	2	0	−20	19	−14	12	2	0	−11	11	−21	16
BA	−35	17	3	−1	0	0	−16	5	4	0	1	−1
	Mortality											
T/A	22	−12	15	−11	3	−3	15	−8	26	−12	28	−17
VOL	3	−2	6	−6	6	−6	3	−2	4	−3	22	−16
QMD	−7	5	−3	2	1	0	−4	4	−8	4	−2	1
THT	−2	1	2	0	0	−1	−1	1	1	0	0	−2
BA	5	−3	8	−8	5	−5	5	−2	6	−4	23	−16
	Crown ratio											
T/A	0	0	0	0	0	0	0	0	0	0	0	0
VOL	−1	0	0	0	0	0	0	0	0	0	0	0
QMD	0	0	0	0	0	0	0	0	0	0	0	0
THT	0	0	1	0	0	0	0	0	0	0	0	0
BA	0	0	0	0	0	0	0	0	0	0	0	0

Table 5—Percentage change in sensitivity indicators resulting from ±10 percent bias of selected input variables.

	Crown ratio				Height				D.b.h.			
	100 years		200 years		100 years		200 years		100 years		200 years	
	−10	10	−10	10	−10	10	−10	10	−10	10	−10	10
							-Percent-					
T/A	3	−2	3	−2	0	0	0	0	5	−4	7	−2
VOL	−5	4	−5	4	−4	3	−2	2	5	−7	3	−7
QMD	−4	3	−4	3	0	0	0	0	0	0	−2	−2
THT	0	0	0	0	−2	3	−1	1	0	0	2	−2
BA	−4	4	−4	4	−1	0	−1	1	5	−5	4	−5

Table 6—Percentage change in sensitivity indicators when measurement precision is varied from the norm for selected input variables.

	Crown ratio				Height				D.b.h.			
	100 years		200 years		100 years		200 years		100 years		200 years	
	20	33	20	33	2	5	2	5	1	2	1	2
			-Percent-				-Ft-				-Inches-	
T/A	−3	3	−2	1	0	0	0	0	−1	0	0	1
VOL	0	0	0	0	0	0	0	0	2	0	0	−2
QMD	2	−3	0	0	0	0	0	0	1	0	0	−1
THT	0	0	0	0	0	0	0	0	0	0	0	−1
BA	0	0	0	0	0	0	0	0	0	0	0	−1

that here values of independent variables have been varied while the models perturbed in the first example controlled rate of change of the values. Thus, the 2 to 5 percent sensitivities observed when the input variable crown ratio is varied by 10 percent is not inconsistent with the at most 1 percent change in sensitivity indicators when the crown ratio model was perturbed plus or minus 10 percent.

These results have a potential impact on the way height, crown ratio, and d.b.h. are measured when data are being obtained for the sole purpose of running FVS. Height of standing trees is commonly measured using some device to measure angle to tree top and some measure of distance or length (either distance from tree or angles to the top and bottom of a height pole of known length). Obviously, heights are not always measured accurately to the nearest 1 foot using these procedures. However, the lack of sensitivity to measuring heights to the nearest 5 feet suggests that these current methods of measurement provide adequate accuracy (as long as the measurements are not biased). Crown ratio is a subjective measurement that requires determination of where the effective base of the crown is. Current practice is to measure crown ratio to the nearest 10 percent. The results of this analysis show that a bias of 10 percent in the measurement of crown ratio results in a 2 to 5 percent change in all sensitivity indicators except top height. Changing to measuring crown ratio as one of three classes resulted in no change in total cubic volume, top height, or stand basal area and 1 to 3 percent changes in trees per acre and quadratic mean diameter. Because we cannot consistently measure crown ratio to the nearest 10 percent, little would be lost by using only three classes (0 to 33 percent, 33 to 67 percent, 67 to 100 percent). If this change were to be adopted, the crown ratio models should be refitted using the new measurement scale. Lack of sensitivity to measuring d.b.h. with 2 inch diameter classes (as opposed to current practice of measuring to the nearest 0.1 inch) suggests that it may not be necessary to measure d.b.h. as precisely as it is currently measured.

Discussion and Conclusions

FVS is a powerful tool that may be used to simulate almost any management scenario. However, effective use of the power of the system requires a thorough understanding of how each of the component models works, both independently and when combined to constitute FVS. Sensitivity analysis can help build this understanding and identify aspects of the component models that show the highest potential for return on future research. Thus, sensitivity analysis provides information of value both to model users and to model developers. Model developers obtain information about setting priorities for future research efforts and information that may be used as a component of the model validation/verification process. Model users obtain information to help design inventories needed to collect information required to run the model, to improve their ability to decide if it is appropriate to use the model in a particular situation, and to build the understanding of individual component model performance needed to set up model runs for simulating specific management scenarios.

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Guidelines for Use of FVS Multipliers

David A. Hamilton, Jr.

Abstract—Forest Vegetation Simulator (FVS) multipliers permit the user to tailor model performance to simulate almost any management scenario. Unfortunately, the intuitively logical choice of multipliers is not always the correct choice and could result in biologically impossible predicted growth. Examples that describe the impact of multipliers on simulated stand development are discussed. Guidelines are presented both for the selection of the proper set of multipliers and for the determination of the correct value to assign each selected multiplier.

Multipliers are powerful tools built into most components and variants of the Forest Vegetation Simulator (FVS). They permit users to modify performance of component models to simulate desired effects not otherwise incorporated in FVS. Unfortunately, the intuitively logical choice of multipliers (either the proper set of multipliers or the appropriate value to assign to a multiplier) is not always the correct choice. Improper specification of multipliers can result in biologically impossible patterns of predicted growth. In extreme cases the program may even fail when arguments of intrinsic FORTRAN functions take on values outside their permitted range.

This paper is based on analyses made with the Inland Empire variant of FVS. However, similar comments and recommendations may be made about most of the variants. More details may be found in Hamilton (1994).

FVS includes four types of multipliers, each of which affects model performance somewhat differently. I deal here with the set of multipliers that modify performance of individual component models and are applied after calibration. These multipliers include HTGMULT (large tree height increment multiplier), BAIMULT (large tree basal area increment multiplier), MORTMULT (mortality multiplier), CRNMULT (crown ratio increment multiplier), REGDMULT (small tree diameter increment multiplier), and REGHMULT (small tree height increment multiplier). Parameters control the way these multipliers affect component model performance. For the mortality multiplier, parameters define the species affected, the projection cycles for which the multiplier will be in effect, and the diameter range of trees the multiplier will affect. Parameters for the other multipliers are the same as for the mortality multiplier except that the diameter range cannot be specified.

For this analysis, I modified the parameters for all the multipliers so that different multipliers may be specified

for up to four diameter ranges in any projection cycle. I also modified my version of the program to include CRNMULT (which is available in most variants but not in the Inland Empire variant). The examples I discuss make use of these modified multipliers. Although these modified multipliers are not available in current versions of FVS, the author could assist users needing to implement such code in their copies of the program.

Problems arising from the intuitive selection of multipliers to accomplish specified results occur primarily because individual component models are not independent. Thus, determining the proper set of multipliers and the proper value for selected multipliers for any given scenario requires a thorough understanding of the component models and of interactions between component models. For example, for trees 3 inches diameter at breast height (d.b.h.) and larger, basal area increment is predicted as a function of d.b.h. and a set of individual tree and stand characteristics (not including height), and height increment is predicted as a function of height, d.b.h., d.b.h. increment, species, and habitat type. For these trees, a basal area increment multiplier will affect both basal area increment and height increment, while a height increment multiplier will affect height increment but will have only a minor affect on d.b.h.

A second example that could have a significant affect on multipliers is the way height increment is estimated for trees in the range 2 to 10 inches d.b.h. (1 to 5 inches for lodgepole pine). To provide for a smooth transition between small tree and large tree models at the 3 inch boundary, trees in this range use a weighted average of estimated height increments. Thus, to achieve a desired change in height increment for trees in this diameter range, it is necessary to use multipliers for both small tree and large tree height increment, even when all trees are either in the large tree or small tree category.

Response to Multipliers

The examples in table 1 show how the Inland Empire variant of FVS responds when multipliers are applied to component models. The intention is to cause a 20 percent increase in both height and basal area increment. To deal with the effect of random variation in FVS output (Hamilton 1991), all results are based on the average of 20 replications of simulated stand development. In each example, model response is demonstrated by assigning a value of 1.2 to the height increment multiplier, to the diameter increment or basal area increment multiplier, or to both multipliers. The first example simulates the development of a 30 year old ponderosa pine plantation on a *Pseudotsuga menziesii/ Physocarpus malvaceus* habitat type for a single 10 year projection cycle. All trees on this stand are greater than 3 inches d.b.h.

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Table 1—Impact of multipliers on performance of component models when applied at various times and in various combinations.

Stand age during simulation	Multiplier				Change in diameter	Change in height
	HTGMULT	BAIMULT	REGHMULT	REGDMULT		
					------ -Percent - - - - - -	
30 to 40	1.2	1.2			19.5	32.4
	1.2				0.0	16.2
	1.2		1.2		0.0	20.0
		1.2			17.2	13.4
		1.2	1.2		19.6	17.1
0 to 19			1.2		14.7	18.8
(3 model				1.2	10.7	−1.2
cycles)			1.2	1.2	24.0	16.0
	1.2[a]	1.2	1.2		18.9	20.9

[a] Applied only to trees less than 3 inches d.b.h.

If component model structure is ignored, the seemingly logical choice of multipliers needed to simulate a 20 percent increase in both height and basal area increment would be a large tree height increment multiplier and a large tree basal area increment multiplier. In the examples this results in an increase of 19.5 percent in diameter increment and an increase of 32.4 percent in height increment. A large tree height increment multiplier, when applied as the only multiplier, results in a height increment increase of 16.2 percent. Diameter increment is unaffected.

When a small tree height increment multiplier is added, the total height increment increase rises to the intended 20 percent. When only a large tree basal area increment multiplier is applied, diameter increment increases 17.2 percent and height increment increases 13.4 percent. When a small tree height increment multiplier is added, diameter increment increases 19.6 percent and height increment increases 17.1 percent. This is the set of multipliers that comes closest to satisfying the objective of a 20 percent increase in both height increment and basal area increment.

Projections made with these multipliers in effect for more than a single 10 year projection cycle can be expected to produce larger changes in both height increment and basal area increment for the first few cycles. However, over a 100 year projection, feedback mechanisms built into individual component models lead to "normal" patterns of stand development as long as multipliers are not excessively large (or small) (see "Guidelines for Sensitivity Analysis of FVS" by Hamilton, this proceedings).

The second example in table 1 examines the impact of multipliers on the development of a stand made up of small trees in a ponderosa pine plantation. The simulation is run from age 0 to age 19. Site conditions are assumed to be the same as for the first example. Projections are made from age 0 to 8, from age 8 to 14, and from age 14 to 19. During the final cycle, many of the trees grow over the 3 inch d.b.h. boundary, resulting in a transition from small tree models to large tree models. When only a small tree height increment multiplier is applied, diameter increment is increased 14.7 percent and height increment increases 18.8 percent. Using only a small tree diameter increment multiplier results in a 10.7 percent

increase in diameter increment and a 1.2 percent reduction in height increment.

The effect of the diameter increment multiplier applied to small trees differs from that observed in the previous example for large trees because of the way FVS calculates diameter increment for small trees. For small trees, diameter is estimated as a function of height and a measure of stand density (crown competition factor). To estimate diameter increment, this function is used to estimate diameter at the beginning and ending of the projection cycle as a function of the height at the beginning of the cycle and the projected height at the end. The difference between these two diameters is the estimated diameter increment. The small tree diameter increment multiplier is applied to this value. Because height is not a function of diameter for small trees, there is no compounding of the effect of a small tree diameter increment multiplier when projections are made for multiple cycles. Using both small tree height and diameter multipliers results in a 24.0 percent increase in diameter increment and a 16.0 percent increase in height increment.

Thus, using both height and diameter increment multipliers on the same small trees still results in a double counting of one of the effects (diameter increment is accounted for twice in this example). Using a large tree basal area increment multiplier, a small tree height increment multiplier, and a large tree height increment multiplier (applied only to trees less than 3 inches d.b.h.) results in an 18.9 percent increase in diameter increment and a 20.9 percent increase in height increment. As was true for the first example, this set of multipliers comes closest to satisfying the objective of a 20 percent increase in both height increment and diameter increment.

These examples highlight potential problems when an intuitively logical set of multipliers is incorrectly applied. They also provide guidelines to identify the correct multiplier values needed to simulate a desired effect. They demonstrate that usually a desired increase of X percent in height increment and Y percent in basal area increment cannot be simulated with height and basal area multipliers of 1.X and 1.Y, respectively. Instead, Hamilton and Rehfeldt (1994) suggested that the appropriate values for multipliers

should be estimated using a systematic iterative search procedure in which FVS is used to simulate stand development with iteratively selected values of multipliers. Because of the random variation that occurs within FVS, Hamilton (1994) suggested repeating the estimation procedure four times and averaging the resulting estimated multipliers.

Use of Extreme Multipliers _____

Multipliers may be used to simulate conditions not specifically included in the data sets used for model development. This includes both extrapolating models to make predictions outside the range of available data and simulating management scenarios not represented in the development data base (for example, simulating the impact of using genetically improved planting stock). However, care must be taken when applying multipliers in this way. The example in table 2 is a case when the use of multipliers to simulate a seemingly realistic scenario resulted in model failure (run time errors caused FVS to crash).

In the sensitivity analysis discussed in Hamilton (this proceedings), one of the objectives was to examine model performance under a range of conditions that included extreme values that would test the limits of applicability of the model. The original design of the sensitivity analysis satisfied this objective too well. When a multiplier of 0.1 was applied to the basal area increment model and a multiplier of 1.9 was applied to mortality, run time errors caused the program to crash. Careful examination of model output revealed that the error was caused by unrealistically large simulated individual tree heights (greater than 1,600 feet). By reducing the mortality multiplier to 1.4, the run time errors disappeared. However, examination of model output showed that tree heights greater than 1,600 feet were still being simulated. Eliminating the mortality multiplier resulted in simulated tree heights in excess of 500 feet. Increasing the basal area increment multiplier to 0.3 resulted in a "normal" pattern of simulated heights.

These results suggest that using an extremely small basal area increment multiplier to simulate stand stagnation may result in simulated stand development that is biologically unrealistic. The message to users of multipliers is that any time extreme values of multipliers are used, it would be wise to carefully examine detailed model output. In the preceding example, there were biologically incorrect patterns of individual tree development being simulated even when stand averages appeared realistic (unrealistically tall trees had small sampling weights and thus had little impact on stand top height).

Table 2—Results of using extreme values of multipliers in FVS.

BAIMULT	MORTMULT	Run status	Maximum tree height
			Feet
0.1	1.9	Crash	>1,600
0.1	1.4	Ok	>1,600
0.1	1.0	Ok	>500
0.3	1.9	Ok	Ok

The difficulties experienced in the preceding example were caused because the small tree height increment model does not contain a term that bounds height increment, and because height increment is calculated as a weighted average of small tree and large tree estimates for a range of diameters around 3 inches d.b.h. Thus, when diameter increment is essentially stopped at a d.b.h. close to 3 inches (with a basal area increment multiplier of 0.1), the small tree estimate of height increment increases, slowly at first but more rapidly as the stand progresses through a long simulation (say 200 years). This effect is normally constrained by increasing stand density and by a decreasing weight for the small tree portion of the estimated height increment. With diameter increment stopped, neither of these constraints are in effect. Thus, the small tree estimate of height increment increases without bound as does the weighted average of small tree and large tree estimates.

This discussion represents an extreme example of the level of understanding of component model performance that may be required to safely use multipliers. The key message is that the user must be fully aware of the potential impact of multipliers on model performance if multipliers are to be used with confidence.

Discussion and Conclusions _____

Multipliers provide the means for extending the capabilities of FVS to include simulation of management scenarios not specifically built into the system. Setting up scenarios requires both the selection of the proper set of multipliers and the determination of the value to be assigned to each multiplier. This process must be based on a thorough understanding of the component models that make up FVS. Although the proper set of multipliers may be unique for a particular scenario, some general recommendations may be suggested:

1. If a scenario calls for an increase of X percent in a single model component, the proper multiplier is 1.X (a fertilizer effect might be expressed as an X percent increase in diameter growth for two projection cycles).

2. If the scenario calls for an increase of Y percent in the average stand value of a particular attribute at a specified age, the proper multiplier must be determined by using a systematic iterative search procedure in which FVS is used to simulate stand development for iteratively selected sets of multipliers (Hamilton and Rehfeldt 1994) (genetically improved planting stock would be expected to have a Y percent greater average stand height at age 19 than unimproved planting stock).

3. In general it is incorrect to apply both a height increment multiplier and a basal area increment multiplier to the same trees.

4. The size of the trees to which the multipliers are to be applied is often the deciding factor in the selection process. In most cases the recommendation should be to use the multiplier or multipliers that correspond to the primary submodel for the trees of interest (height increment multiplier for small trees and basal area increment multiplier for large trees).

5. When the intention is to simulate an increase in stand growth without altering the height diameter ratio, the proper set of multipliers is a small tree height increment multiplier, a large tree basal area increment multiplier, and a large tree height increment multiplier that is applied only to trees less than 3 inches d.b.h.

6. Users need to remember the warning about the potential problems that may arise when extreme values of multipliers are used. Any time multipliers are used that result in large changes in component model performance, detailed model output should be carefully inspected for cases where simulated results may not match biological reality.

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Regeneration Models for FVS Variants

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Abstract—The Forest Vegetation Simulator (FVS) predicts forest growth for 19 geographic locations in the United States and Canada. However, only four of the 19 geographic variants have models that simulate the process of regeneration establishment. Considerable work needs to be done to develop regeneration models for all FVS variants. An alternative to designed research studies is to use stand examination inventory data to develop regeneration models. The most important data consideration is to locate and use unbiased inventories. Fortunately, many organizations already collect the data needed to develop such regeneration models. Ideas are presented for designing stand examinations that provide data for regeneration modeling.

Today, mathematical models that predict forest development over time are an integral part of management planning. The Prognosis Model for Stand Development (Stage 1973) is an individual-tree, distant-independent forest growth model that was originally developed for the forests of northern Idaho and adjacent portions of Montana and Washington. The framework of the Prognosis Model has been used to develop variants for other geographic locations using the title of Forest Vegetation Simulator (FVS). FVS variants have the capability to predict forest development and interactions with other forest components such as wildlife, fire, insects, disease, and watershed (Teck and others 1996).

While variants for FVS have been developed for 19 geographic locations in the United States and Canada, regeneration establishment models have only been developed for four variants (Teck and others 1996). They are Inland Empire, Kootantl, central Idaho, and southeast Alaska. A research study was used to collect data for modeling regeneration establishment for the Inland Empire, Kootantl, and central Idaho variants of FVS (Ferguson and Carlson 1993; Ferguson and others 1986). Routinely collected Forest Service stand examination data were used to develop a regeneration model for the southeast Alaska variant of FVS (Ferguson and Johnson 1988). Regeneration models need to be developed for the other FVS variants to predict stocking, density, species composition, and growth of regeneration; to link to models predicting nontree vegetation, watershed considerations, ecosystem dynamics, and wildlife habitat; and to model succession in long-term predictions of forest development.

The process of regeneration establishment is highly variable due to the many chance occurrences that lead to the successful establishment of seedlings. Extrapolating a

regeneration model from one geographic area to another would be highly unreliable because ecology differs considerably among geographic areas. Modelers that are knowledgeable of the distributions of tree species (Little 1971) and forest vegetation by ecological habitat type (Alexander 1988) can appreciate the complex plant communities that would be included in regeneration models. Each FVS variant needs its own regeneration model.

Models predicting regeneration success are needed for natural and human-caused disturbances, for plantation survival, and for advance regeneration in existing stands. Most often, regeneration is initiated by disturbance events such as timber harvest, fire, windthrow, disease and insect outbreaks, and so on. Following a disturbance, new trees become established from seeds or from root and stump sprouts. Planted trees provide stocking on sites where natural regeneration is slow to become established, and planted trees supplement the natural regeneration that does occur. Data on plantation survival would improve the ability to model development of artificially regenerated stands. Advance regeneration are trees that become established in new or existing canopy gaps, or are shade-tolerant species that become established beneath existing overstory trees as a result of natural succession.

Few research studies exist that have been designed specifically to develop regeneration models for FVS variants. Requirements of a large sample size and unbiased stand selection mean that it would take years to develop a regeneration model for each variant. Each variant would need field sampling for 2 to 3 years and several years to fit equations and test the model. Even after a regeneration model is complete, it will be necessary to periodically update equations to account for advances in technology, changes in climate, shifts in management practices, or changes in forests due to disease, insects, fire, and so on.

An alternative to designed research studies is to use stand examination data. Stand examinations are routinely conducted and they should reflect operational regeneration success following natural and human-caused disturbances. This paper discusses the use of stand examination and other inventory data to develop regeneration models for FVS variants.

Data Considerations

The most important data consideration is to locate and use unbiased stand examination data. Stands are scheduled for examinations for a variety of reasons, but some reasons could lead to results that, if used to develop a regeneration model, could result in a biased model. For example, an examination that was scheduled because of the ease or difficulty of obtaining regeneration would result in a biased regeneration model. Good sites that are easier to regenerate might receive earlier and fewer examinations. Sites that are

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more difficult to regenerate might be examined more often to determine the progress of the stand, and examinations might be taken later in the regeneration period.

Another source of bias would be the type of regeneration examination. If good sites more often receive a walk-through examination and poor sites receive a full regeneration examination, good sites will not be well represented in the inventory data. Similarly, in years of decreased budgets, perhaps only poor sites were inventoried because their regeneration success is less certain than on good sites.

Stand examination data could also vary in ways unknown to the modelers. For example, managers could change stand examination standards over time and among locations. A large workload might result in a decision to sample only the regeneration and ignore the overstory trees in a shelterwood harvest. In this case, the manager is determining whether there is enough regeneration to remove the overstory, but if the data are put into a data base, the fact that the overstory was not inventoried may be lost. Thus, inventories that carefully sample not only the regeneration component, but also the residual overstory conditions under which the regeneration developed, should be used.

The modeler has to become familiar with potential sources of data and determine if the data are acceptable to include when fitting a model. Questions must be asked about why stands were examined and how the data were collected. Locating acceptable stand examination data is crucial to developing defensible regeneration models, particularly for equations predicting the probability of stocking.

Suitable datasets may contain several hundred to several thousand stand examinations. The next step in developing a regeneration model is to select a subsample of stands to include in equation development. Stands should be selected in an unbiased manner, yet cover common ecological types, disturbances, and management practices. A stratified random sample works well to select stands while sampling important sources of variation within a geographic area.

Table 1 shows an example information grid that can be used to randomly select stands in central Idaho. The grid uses regeneration method, site preparation, habitat type series, and the number of years since disturbance. Stratifying by regeneration method provides a range of overstory densities. Classification by site preparation method ensures

that site preparations of interest are sampled. Similarly, the selected habitat types are common in central Idaho (Steele and others 1981). Finally, classes for years since disturbance will ensure sampling of a range of stand ages.

Similar information grids could be used to select stands for nonharvest disturbances, such as when regeneration is initiated because the overstory is killed by fires, diseases, insects, weather events, and so on. Modeling regeneration following natural disturbances is increasingly important in today's world.

Another important mode of regeneration is advance regeneration in existing stands. An information grid similar to table 1 could also be used for modeling the occurrence of advance regeneration.

The information grid is only used to select stands. Actual plot basal area, site preparation, habitat type, years since disturbance, and so on, should be used to construct the model. The experimental unit is a small plot, not the stand.

Stands that received a stand examination would be classified into cells in the information grid and then randomly selected for inclusion in equation development. Sample without replacement, so that once an inventory is selected for a stand, an earlier or later inventory is not chosen for the same stand. The number of stands in each cell depends on the number of plots sampled in the stands. An adequate sample size would be about 100 to 150 plots for major cells in the information grid.

Filling all cells in the grid will not be possible because certain combinations do not occur often; an example is underburns in selection regeneration methods. However, plots within stands will represent different cells in the grid because of the heterogeneous nature of stands. Plots within stands can even differ in age when site preparation is done one or more years after a disturbance.

Small plots should be used to sample regeneration. Haig (1931) discusses how the size of plots for regeneration surveys was originally chosen as a function of the density of mature stands. Haig showed that full yields in the western white pine (*Pinus monticola*) type in northern Idaho are reached when there are about 290 trees per acre 7 inches or larger in diameter at breast height. His recommendation was to use a 1/250-acre square plot for regeneration surveys. Whatever plot size is used, it should be in common use for the

Table 1—An example information grid for stratified random sampling for harvested stands in central Idaho. Similar grids could be used to develop regeneration models for natural disturbances (fire, insect and disease outbreaks, and so on) and to predict advance regeneration.

Habitat type series	Number of years since disturbance	Regeneration method and site preparation								
		Clear-cut/seedtree			Shelterwood			Selection		
		None	Mech	Burn	None	Mech	Burn	None	Mech	Burn
DF[a]	1-10	X	X	X	X	X	X	X	X	X
DF	11-20	X	X	X	X	X	X	X	X	X
GF	1-10	X	X	X	X	X	X	X	X	X
GF	11-20	X	X	X	X	X	X	X	X	X
SAF	1-10	X	X	X	X	X	X	X	X	X
SAF	11-20	X	X	X	X	X	X	X	X	X

[a]DF = Douglas-fir series, GF = grand fir series, SAF = subalpine fir series.

geographic area of the FVS variant. Data from ownerships that use different plot sizes cannot be merged to produce equations predicting the probability of stocking. However, inventory data from different plot sizes can be used to estimate density of regeneration.

The reason for using small plots is to be able to predict the distribution of regeneration and seedling density. For example, Wellner (1940) suggested a minimum of 65 percent stocking of $\frac{1}{250}$-acre plots and a density of 1,000 trees per acre in the western white pine type. A lower percent stocking, but the same density, means that regeneration is clumpy with many nonstocked plots. Lower seedling density, but the same percent stocking, means that many plots could become nonstocked through mortality before the stand reaches maturity.

Another point about the distribution of regeneration is that sometimes managers are interested in the distribution of certain species. By identifying at least one tree of each species on plots, it is possible to determine the distribution of each species within the stand. Suppose a manager is interested in thinning a stand to favor Douglas-fir (*Pseudotsuga menziesii*). A regeneration model that predicts the distribution of trees by species can be used to identify the number of well-distributed Douglas-fir in the stand.

Equation Development

The development of equations for FVS regeneration models uses the two-state method of Ferguson and others (1986). In the first state, plots are either stocked or nonstocked. All plots are used to predict the probability of stocking (at least one established seedling on the plot). In the second state, only stocked plots are used to predict attributes of stocked plots, such as trees per plot, number of species, species composition, and seedling heights. During creation of regeneration tree records in a regeneration model, the probability of stocking is used to scale the attributes of stocked plots to a per-acre basis.

Table 2 illustrates the two-state methodology used to predict regeneration. Only five plots are used for illustration

purposes. Usually, more plots are included in an inventory or the regeneration model replicates plots until at least 50 are available for the simulation. A smaller number of plots results in a stochastic prediction while a larger number of plots (or plot replications) results in a more deterministic prediction.

Thus, five sets of equations are needed to develop a regeneration model from stand examination data: probability of stocking, number of trees per stocked plot, number of species, species distributions, and heights of seedlings.

The probability of stocking is a logistic regression equation (Hamilton 1974; SAS 1990) that predicts the probability that a plot will be stocked with at least one established seedling. Predicted stocking is a continuous number in the interval [0,1] (fig. 1).

The distribution of number of trees per stocked plot usually follows a reverse-J shape (fig. 2). It is important to model the distribution of trees per stocked plot, which can be done with a Weibull distribution (Bailey and Dell 1973). A pseudo-random number can then be used to make an unbiased, yet discrete, choice of the number of trees on the plot.

The number of species on stocked plots is conditional on the number of trees on the plot (fig. 3). For example, a plot with two trees can have one or two species (assuming that two or more species are possible). Equations for the number of species on the plot can be either probability equations or proportions calculated from subsets of the data (for example, proportions for each cell in the information grid).

Once the number of species is chosen, the species can be selected. In more complex ecosystems, the probability of each species can be calculated with logistic regression. For simpler ecosystems, proportions can be calculated from sampled distributions. Figure 4 shows the distribution of ponderosa pine (*Pinus ponderosa*) and Douglas-fir on Douglas-fir habitat types in central Idaho.

Seedling heights can be predicted from plot and stand variables using linear regression, or the distribution of heights can be modeled with Weibull equations. Figure 5 shows the distribution of heights for Engelmann spruce (*Picea engelmannii*) for two time periods in central Idaho.

Table 2—Example prediction of regeneration on five $\frac{1}{300}$-acre plots. The probability of stocking (PS) is used to scale attributes of stocked plots to a per-acre basis. N is the number of plots in the projection; N is 5 in this example.

Plot No.	Probability of stocking (PS)	Number of trees/stocked plot (TPSP)	Number of species	Selected species	Seedling heights	Plot density = (PS*TPSP*300)/N
1	0.65	3	2	DF(2)	3.9, 2.1	117.0
				PP(1)	3.5	
2	0.47	4	3	PP(2)	1.5, 1.2	112.8
				LP(1)	2.6	
				DF(1)	1.0	
3	0.34	1	1	LP(1)	2.4	20.4
4	0.54	1	1	PP(1)	1.8	32.4
5	0.40	2	1	LP(2)	4.6, 2.1	48.0
	$\bar{x} = 0.48$					$\Sigma = 330.6$
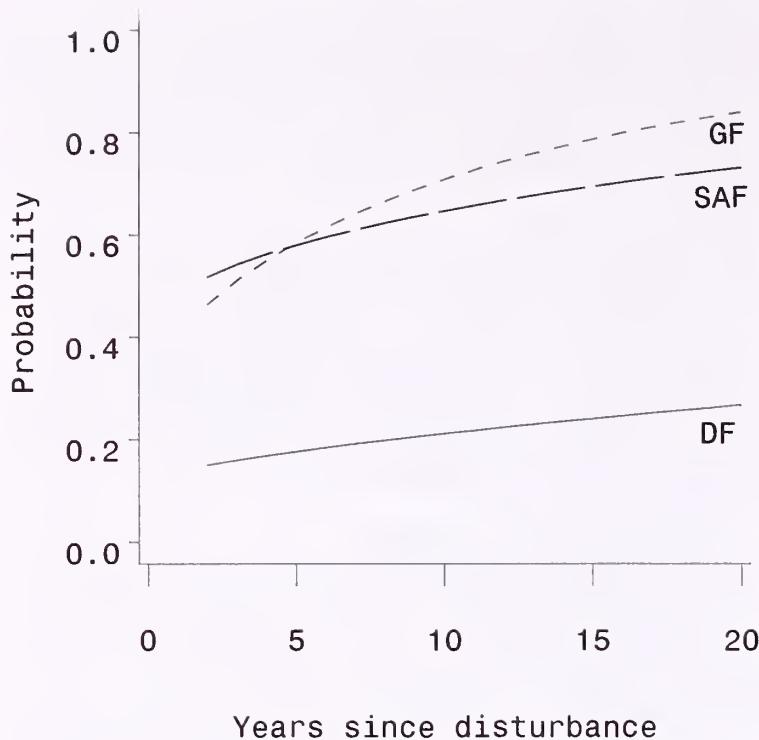
Figure 1—Probability of stocking (at least one established seedling on a 1/300-acre plot) for Douglas-fir, grand fir (*Abies grandis*), and subalpine fir (*Abies lasiocarpa*) habitat types. Equations are from Ferguson and Carlson (1993).

Inventory Data for Regeneration Models

Independent variables that are useful in predicting regeneration may vary from geographic area to geographic area, but many ownerships already collect data that can be used to develop regeneration models. Published regeneration studies can be helpful in designing regeneration inventories. The ability to develop high quality regeneration models from stand examination data can be enhanced by defining standards for consistent regeneration inventories. Previously discussed was the need to inventory small plots and use a plot size that is commonly used in the geographic area. Following are other recommendations for regeneration inventories, which can also be used to choose appropriate data to include in regeneration models:

- Record attributes of individual plots, such as slope, aspect, ecological habitat type, site preparation, topographic position, overstory density, and overstory species composition. Recording individual plot attributes enables modeling of heterogeneous stands and it helps make each plot an independent sampling unit.
- Take the inventory of the overstory from the same point as the regeneration plot.
- Record some variables at the stand level, such as elevation and history of management activities.
- Explicitly define the data that are to be collected and set standards for data collection. For example, when is a plot stocked (species, sizes, ages), what are the units of measure for tree heights, and is current year's growth included in the measurement of height?
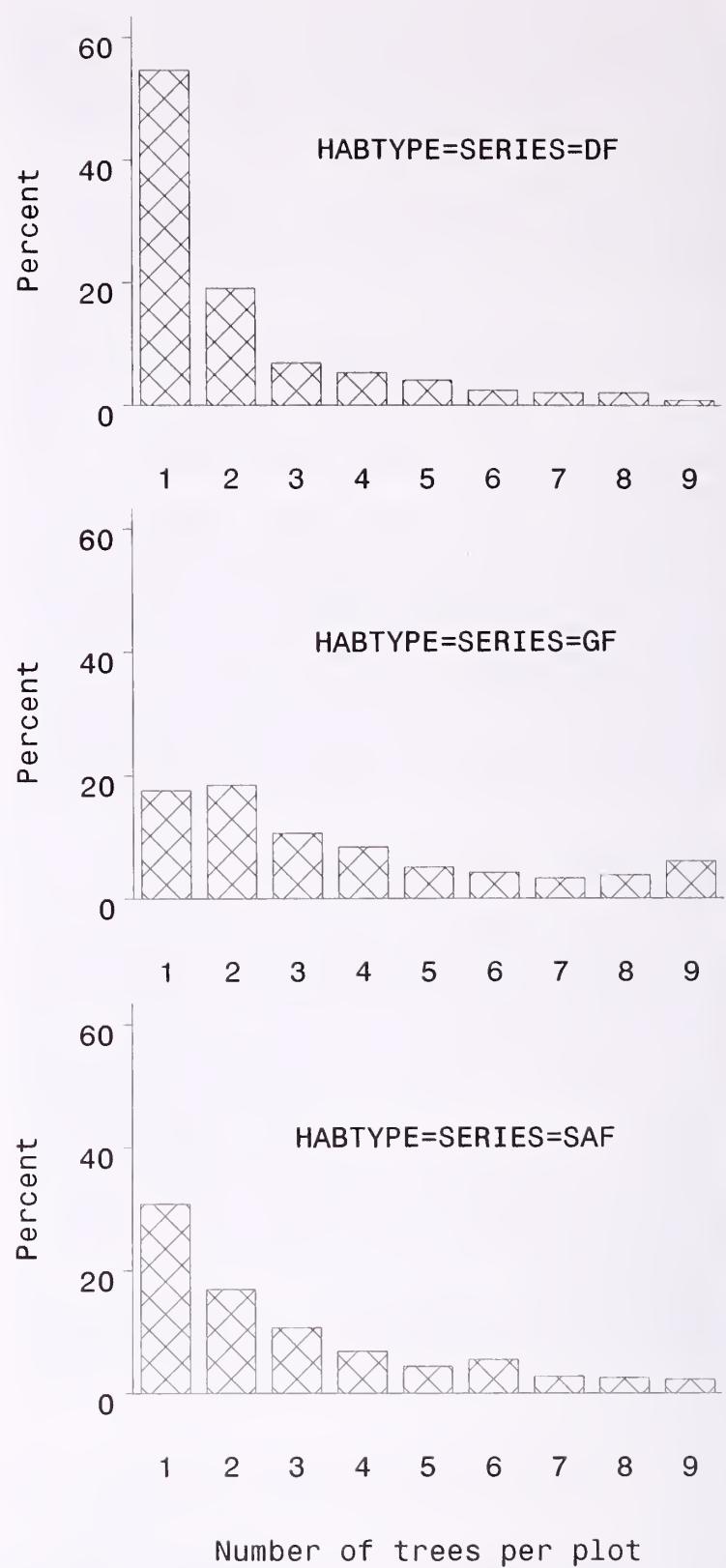
Figure 2—Distribution of the number of trees per stocked plot for Douglas-fir, grand fir, and subalpine fir habitat types. Values greater than nine trees per plot are not shown. Data are from Ferguson and Carlson (1993).

- Count the number of established trees by species. For species that regenerate in large numbers, estimate the number of stems on the plot rather than truncating the count.
- Identify regeneration that results from root and stump sprouts. If possible, record the diameter of the stump of
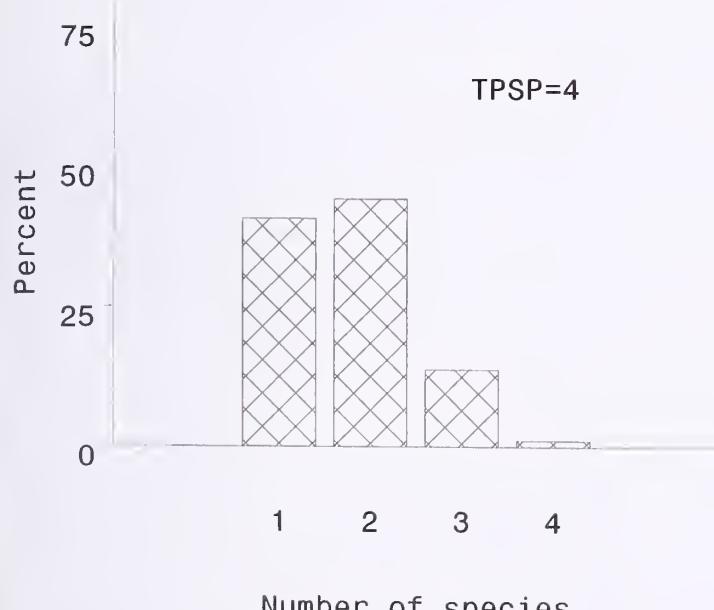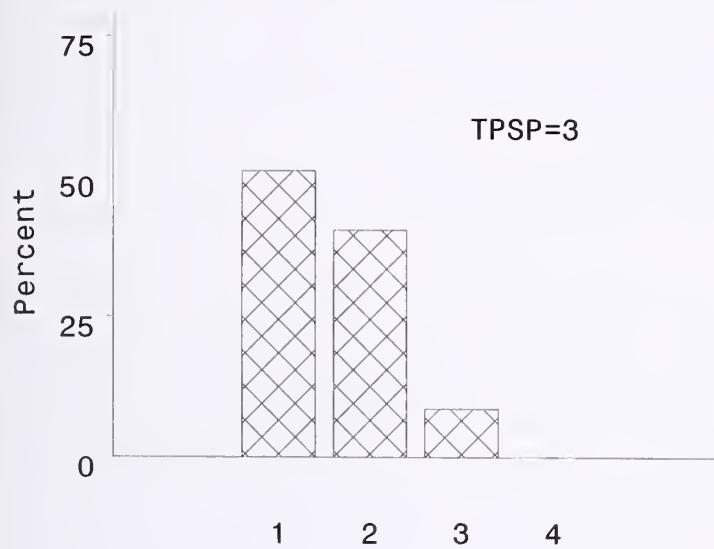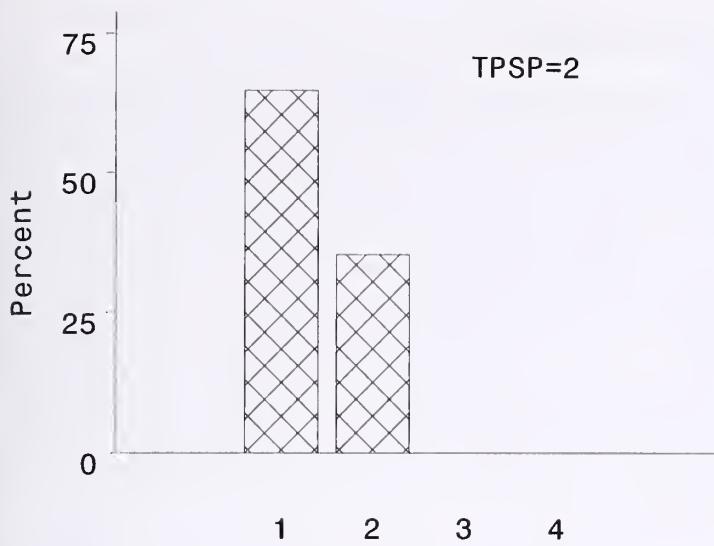
Figure 3—The number of species per stocked plot, conditional on the number of trees per stocked plot (TPSP). These data are for Douglas-fir habitat types (Ferguson and Carlson 1993).
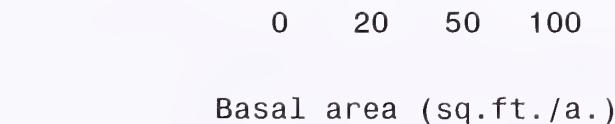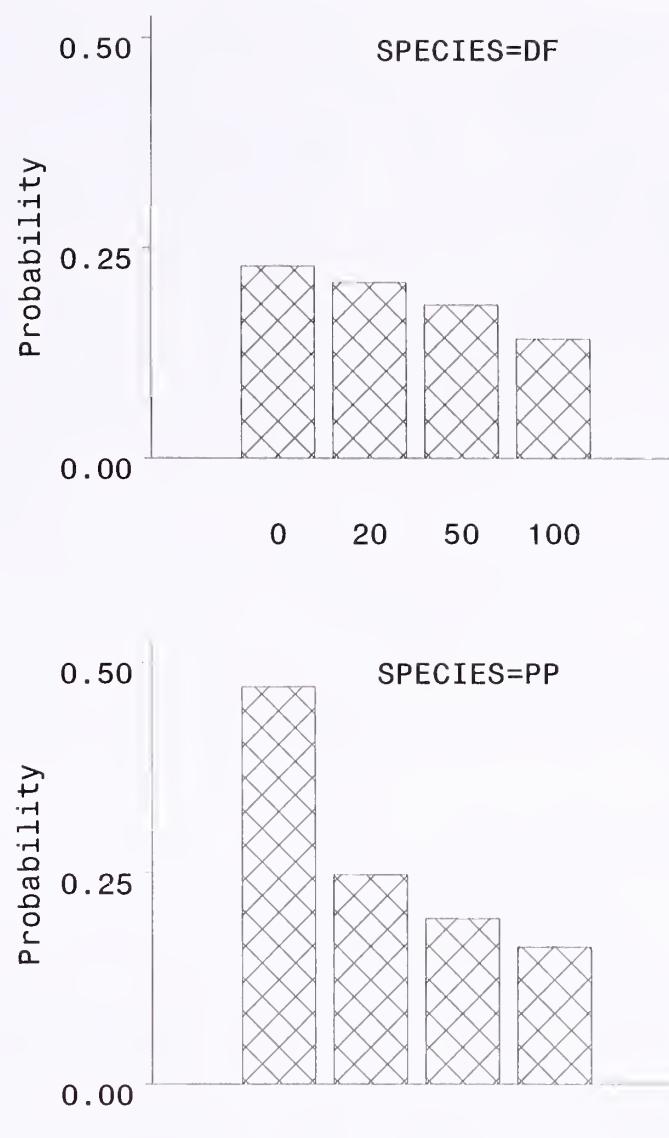
Figure 4—Species distributions for ponderosa pine and Douglas-fir on Douglas-fir habitat types (Ferguson and Carlson 1993).

the parent tree. (In some geographic areas, published equations may already exist that predict the number and size of sprouts.)

- Keep good records of stand history and management activities. Examples are year of disturbance, type and year(s) of site preparation(s), year(s) of planting, species planted, and seed sources for planted species. In some cases, the history of the previous stand may be important for predicting regeneration; factors may include density and size of species that sprout, number and size of trees that have serotinous cones, and history of insects and diseases.

- If possible, spread regeneration examinations out among a number of stand ages. Having all stand ages represented in the regeneration period will allow accurate fitting of equations and average over year-to-year variation in weather, seed crops, insects and disease, and so on.
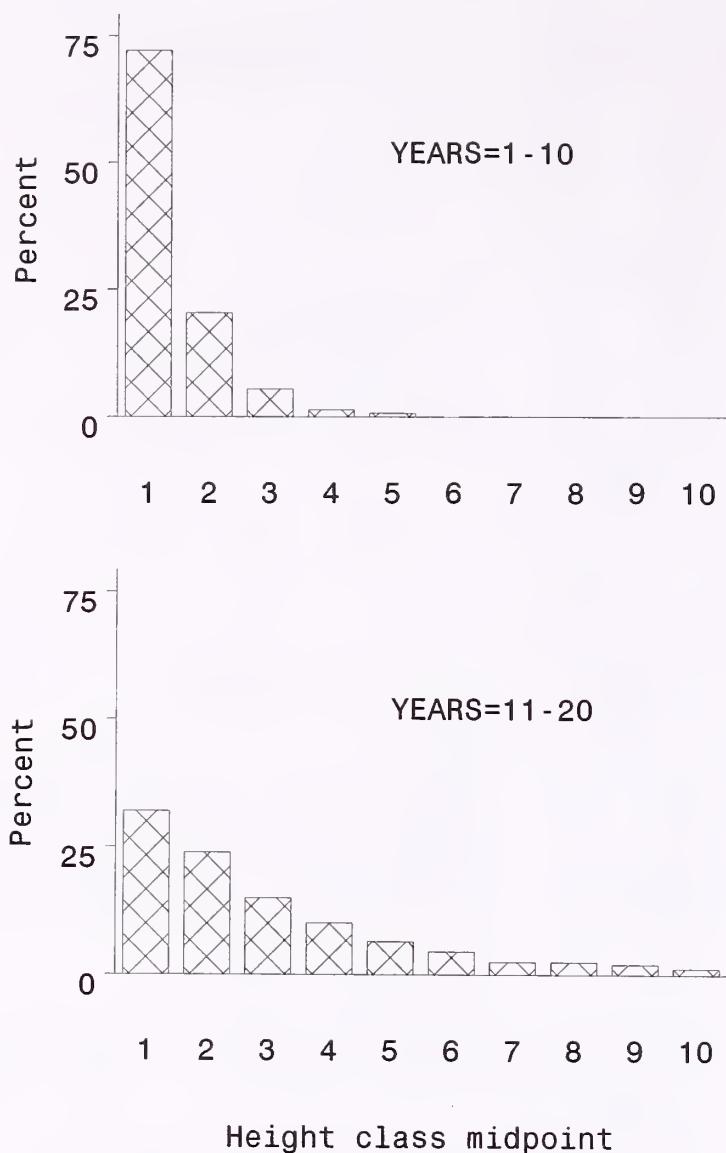
Figure 5—Distribution of heights of Englemann spruce in central Idaho for two classes of stand ages, 1 to 10 years and 11 to 20 years. Data from Ferguson and Carlson (1993).

- Collect additional data that could be used for other FVS models. This could be done at little cost. Record percent cover and average height of nontree species on the plot for use in the SHRUBS model (Moeur 1985). Record height increment on seedlings and saplings. Height increment data could be used to construct equations predicting periodic height increment for seedlings and saplings.
- Record data on plantation survival and growth for use in modeling artificially regenerated stands.

From a modeler's view, the best scheduling of stand examinations would be a predetermined sequence of examinations that begin following a disturbance. The predetermined inventories would allow for flexibility in scheduling examinations; say at 5±2 years, 10±2 years, and 15±2 years. Field crews would then sample the stands representatively so that areas to be sampled are not determined by the expected outcome of regeneration success.

Discussion

Two options for developing regeneration models for FVS variants have been discussed. The first option is research studies specifically designed to collect the necessary data (for example, Ferguson and Carlson 1993; Ferguson and others 1986; Seidel 1979; Stein 1981). The second option is to use routinely collected stand examination data. High quality stand examination data can be used to develop regeneration models, as was done for the southeastern Alaska variant of FVS (Ferguson and Johnson 1988). The advantage of using existing stand examination data is that it has already been collected, and the examinations sample common regeneration methods over a wide range of stand conditions.

The quality of inventory data can be a concern when data are collected to different standards. Concerns can be alleviated by specifying minimum standards for consistent inventories. Providing good training to field crews will help them collect the high quality data needed for regeneration modeling. Many forest land owners now provide ecological training and retain the same crews from year to year, both of which improve the quality of stand examinations.

Sampling of stand ages should be spaced, where possible, so that inventory samples are not clustered in time, and so that important stages in the regeneration process are not missed. Sampling needs to be spread throughout the regeneration period to improve accuracy of predictions. Gaps in the data 2 to 3 years long would not be a problem. Gaps in stand ages longer than about 3 years may mean that biologically important data are being missed. For example, in the southeastern Alaska variant of FVS, the number of seedlings per acre increases until about 15 years after harvest, then begins to decline because of intertree competition (Ferguson and Johnson 1988). Standard examinations taken at 10 and 20 years would miss this biologically important peak in density.

The good news is that most ownerships already collect the data needed to model regeneration. If not, their inventory procedures could easily be modified to collect the necessary data. The Northern Region of the Forest Service modified their stand examination procedures after release of the regeneration model for the Inland Empire variant of FVS (Ferguson and others 1986). They added plot slope, aspect, ecological habitat type, topographic position, type of site preparation, and distance to seedwall. In addition, nontree vegetation is described as percent cover and height by species. The Northern Region also has different levels of stand examinations, from standard examinations to quick plots to walk-through examinations. Because they code the level of the examinations, users of the data know the standards that were used to collect the data.

Properly collected stand examination data can be used to certify stocking, to assess growth rates, to determine plantation success, to look for thinning needs, and to link to other forestry resources. These data can also be used to develop regeneration models. It is important that we keep good historical records and conduct standardized inventories. The resulting data can be used to monitor success of silvicultural treatments and construct models of forest growth.

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The Single-Tree Stand Growth Simulator PROGNAUS

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Abstract—PROGNAUS (PROGNosis for AUStria) is a forest stand growth model designed to simulate the growth and development of both pure even-aged and mixed-species uneven-aged stands using a distance-independent individual tree methodology. Models were developed from remeasured permanent plot data (45,000 sample trees on approximately 5,500 plots) from Austrian National Forest Inventory data collected from 1981–1990. PROGNAUS currently consists of a basal area increment model, a height growth model, a crown ratio model, a mortality model, and an ingrowth model for all major forest species in Austria. Because PROGNAUS must be able to simulate the development of uneven- as well as even-aged stands, site index and age are intentionally not used as predictors. A model validation trial using independent data from research thinning trials (1977–1992) indicated that the simulator predicts both the basal area increments and mortality rates in mixed Norway spruce-Scots pine stands quite well over the entire observation period. Ongoing simulator development is expanding the capabilities of the regeneration and stand treatment features, as well as developing an improved height increment model.

European forest management has traditionally relied on yield tables to estimate yields for forest management decisions and for forest planning (Kurth 1994). Nevertheless, the main assumption of yield tables, that all stands are pure and even-aged, is becoming increasingly untrue in Central European forests. Smaltschinski (1990) reports from the National German Forest Inventory that 41 percent of Germany's forest stands are mixed, defined as a stand with more than 10 percent of the volume in at least one other species. The latest Austrian National Forest Inventory found 36 percent of the stands were mixed, defined as conifer stands with more than 20 percent of broadleaf species, and as broadleaf stands with more than 20 percent of conifer species (Schadauer 1994). The amount of mixed stands is higher than this figure if mixtures of only conifers or only broadleaf species are considered. The shift from even-aged management is also evident. In the recent Austrian Forest Inventory, only 47 percent of the harvests were clearcuts of more than 0.05 ha (Schieler and Schadauer 1993). Furthermore, only 45 percent of the inventory plots were even-aged enough to allow usual site index determination.

This shift away from classical even-aged forest management renders existing yield tables increasingly unreliable. One way to forecast yields for uneven-aged mixed-species stands is to develop stand growth models that operate at the individual tree level. Unfortunately, there are few single-tree growth models developed for uneven-aged mixed stands in Central Europe (examples are Eckmüllner and Fleck 1989; Pretzsch 1992), and each requires site index to derive potential height growth.

One of the few forest growth models that does not need site index, age, or mapped tree coordinates is the widely used Stand Prognosis Model (also known as the Forest Vegetation Simulator, FVS) developed by Stage (1973) and Wykoff and others (1982). Site information in FVS is obtained from topographic descriptors (elevation, slope, aspect) and climax vegetation classification (habitat type). Wykoff and Monserud (1988) demonstrated that the FVS approach for representing site quality performs as well as approaches using traditional site index information. Based on the widespread success of the FVS approach (Teck and others, this proceedings), we began with the premise that a high quality and representative Austrian forest inventory coupled with the FVS modeling approach should produce a useful and broadly applicable stand simulation model for Austrian forests. The result is PROGNAUS (Sterba and others 1995a, b), the first stand management model in Europe capable of predicting the development of both pure even-aged plantations and mixed-species uneven-aged stands without any need of potential growth estimation from site index systems.

Data

Model parameters were estimated using data provided by the Austrian National Forest Inventory (Forstliche Bundesversuchsanstalt 1981). Redesigned in 1981, this inventory is a systematic permanent sample over the whole of Austria, with a 5 year remeasurement interval. The sample plots are clustered at the four corners of a 200 by 200 m square. The clusters themselves are systematically distributed over Austria on a 3.89 km grid. In a given year every fifth cluster is remeasured, ensuring a representative sample of all Austrian forests each year. The total inventory comprises 5,500 clusters, consisting of 22,000 permanent plots. We restricted ourselves to the 5,416 forested plots not crossed by roads and in a single ownership.

Permanent sample plots were established from 1981 to 1985. Plot centers were marked by a hidden iron stake buried underground that is relocated by a metal detector. Trees with a diameter at breast height (D, 1.3 m) larger than 10.4 cm were selected by angle count sampling using a basal area factor of 4 m^2 per ha. Only trees with a D between 5 and 10.4 cm were measured within a circle of 2.6 m radius located at plot center; note that 2.6 m is the limiting distance for a 10.4-cm tree with a 4 m^2 per ha basal area factor. Sample trees were recorded by their polar coordinates and marked by a nail at the base of the tree. The nail is used with a 1.3 m pole to locate breast height. Diameters were measured with a caliper, with the leading edge pointing to plot center. This hidden plot design was used to eliminate research plot bias (Bruce 1977) and ensure that the Forest Inventory is representative of growing conditions and forest management throughout Austria.

At plot establishment, the following data were recorded for every sample tree: species, D to the nearest millimeter, total height and the height to crown base to the nearest decimeter, and distance and azimuth from plot center. The survival status was also recorded (live, dead), with natural mortality distinguished from harvesting mortality. Site descriptors (slope, aspect, elevation, slope position, soil depth, humus depth, soil type, vegetation class, moisture class, geographic district) were recorded on a fixed 300 m^2 plot. Regeneration on this plot was broadly classified into one of three developmental stages: (1) no regeneration, (2) regeneration with average height less than 1.3 m, and (3) regeneration with average height greater than 1.3 m. Plots were remeasured from 1986 to 1990, exactly 5 years after establishment.

Stand Development Models

Basal Area Increment

Because of desirable properties with the error structure (homogeneous variance, errors normally distributed), Monserud and Sterba (1996) chose Wykoff's (1990) logarithmic model for basal area increment. This formulation is common in many FVS variants. In general, the logarithm of increment is expressed as a function of tree size, competition, and site variables for each species:

$$\ln(BAI) = a + b \cdot SIZE + c \cdot COMP + d \cdot SITE + \epsilon \qquad (1)$$

with BAI the 5 year basal area increment (outside bark), a the intercept, b the vector of coefficients for the tree size variables, c the vector of coefficients for the competition variables, d the vector of coefficients for the site variables, and ϵ a random error $\sim N(0, \sigma^2)$. Size variables are diameter at breast height (D) and its square, and crown ratio (CR). Competition variables are basal area in larger diameter trees (BAL), and crown competition factor (CCF). Continuous site variables are slope, aspect, elevation, and the depths of the F and H humus horizons. Discrete site descriptors require 0-1 dummy variables to indicate their presence or absence. These descriptors include groupings for soil depth, soil moisture, slope position, soil type, vegetation type, and geographic growth districts. Monserud and Sterba (1996) provide full functional detail.

Overall, most of the variance explained by (1) is due to size factors (diameter, crown ratio) (14 to 47 percent). The next most important contribution comes from competition variables, primarily basal area in larger trees (0 to 13 percent; see table 11 in Monserud and Sterba 1996). Only 2 to 6 percent of the total variation is explained by site factors. The total variance explained by the model (R^2) lies between 20 and 63 percent. The model does a good job in explaining the variation in basal area growth for four of the six major species (spruce, beech, fir, and oak) and two minor species (black pine and the other broadleaf species), all with R^2 over 50 percent. The model does a moderate job of explaining variation for the remaining two major species (Scots pine and larch, with R^2 = 33 percent and 43 percent, respectively). Only for the high elevation stone pine does the model do a poor job of explaining basal area growth (R^2 = 20 percent); competition effects were not even detectable for this subalpine species. Because Scots pine and stone pine have the least amount of variation in basal area increment, it is not surprising that they are the most difficult species to predict precisely.

Height Increment

The Austrian National Forest Inventory remeasures the heights of every fifth sample tree. Using these data for Norway spruce, the major species in Austria, Hasenauer and Monserud (1997) concluded that measurement errors in height increment, obtained by subtraction of remeasured heights on standing trees, are so large that the underlying height increment signal is nearly hidden (R^2 = 0.14), even with a sample as large as 7,500 Norway spruce. For other species the R^2 was even less, indicating that in general the signal (height increment) is buried by noise (measurement error). The key conclusion is that an accurate height increment model (such as Stage 1975) can only result from felled-tree data, where the variable of interest, height increment, is observed directly.

As an interim measure, PROGNAUS is currently using the height increment model of Knieling (1994), which is based on remeasured total heights on research plots:

$$\Delta H = b_0 + b_1 \Delta D / D + b_2 \Delta D + b_3 / D + b_4 H + b_5 D \qquad (2)$$

Crown Ratio

Crown length, calculated as the difference between total height and the height to the crown base, is one measure of tree vigor. A closely related dimensionless measure is crown ratio, defined as the crown length divided by the total tree height. Crown ratio is mainly driven by stand density and the social position of a tree within a stand. Note that change in crown ratio is not available because height to crown base was not remeasured after the initial inventory. Hasenauer and Monserud (1996) used the following logistic function to predict crown ratio, insuring that predictions of CR are bounded between 0 and 1:

$$CR = (1 + e^{-(a + b \cdot SIZE + c \cdot COMP + d \cdot SITE)})^{-1} \qquad (3)$$

where the size variables are the height/diameter ratio H/D, height H, and squared diameter D^2; the competition variables

are BAL and the logarithm of CCF; the site variables are elevation, slope, and aspect; and e is the base of natural logarithms.

The total variation explained by model 3 varied from 49 percent for larch to 17 percent for the "other broadleaf species" (table 5 in Hasenauer and Monserud 1996). The model explained 41 percent of the variation in crown ratio for the principal species, Norway spruce. The model explained less than a quarter of the variation for all the broadleaf species and for stone pine.

The effect of the SIZE variables is approximately equal in importance to the COMP variables for spruce, fir, larch, and stone pine. In almost all cases the most important size variable was the H/D ratio. For Scots pine and black pine the effect of COMP is more important than SIZE. The opposite is true for all of the deciduous species (beech, oak, others). The set of topographic site factors (SITE) explained the least amount of variation, less than 10 percent in all cases. Although topographic site factors explained a relatively low amount of variation, they are important because they account for local and regional differences in crown ratio predictions. For example, the contrast between the characteristic long, narrow crowns of high-elevation spruce versus the fuller, normal spruce crowns on low- to mid-elevation sites is likely due to genetic differences that are aliased with elevation.

Hasenauer and Monserud (1996) tested the crown ratio model with independent data with over 3,500 trees from 43 permanent research sample plots that are representative of common stand and treatment conditions in Austria. Species composition consisted of the four main species in Austria: Norway spruce, white fir, Scots pine, and beech. Results of the independent validation test indicated that almost no trends exist between the model variables and the differences between predicted and observed crown ratios. For fir, a slight relationship existed between residuals and height (r^2 = 8 percent), and the mean difference was an overestimate of 0.061 in crown ratio. In these permanent plots, fir was small and mainly suppressed, a condition not representative of the entire Austrian National Forest Inventory. For Norway spruce and Scots pine, no problems with overall bias or bias in the slope coefficients are indicated. The model for beech overpredicted crown ratio by 8.5 percent, which Hasenauer and Monserud (1996) expected for this broad-leaved species because of a different definition of crown base in the validation data base versus the Forest Inventory definition. For beech, the residuals exhibited no relation with the input variables.

The crown ratio model appears to be well behaved and robust for all types of stands, from pure to mixed-species composition, and from even-aged to uneven-aged structure. Analyses of the residuals from permanent research plots representing a wide variety of thinning treatments indicate that the effect of management seems to be adequately represented by the model.

Mortality

The Austrian National Forest Inventory collected high quality information on individual tree survival and mortality. Repeated measurements from the period 1986 through 1990 found the 5 year mortality rate is 4.7 percent for all species combined, which corresponds to an annual rate of 1.0 percent. The most common species, Norway spruce, had a 5 year mortality rate of 4.4 percent. Conifer mortality rates (5 year) varied between a high of 6.1 percent for fir and 2.9 percent for larch. The 5 year rate was 4.3 percent for beech, 3.2 percent for oak, and 8.0 percent for all other broadleaf species combined.

Although any cumulative distribution function could be used to model the probability of mortality, the logistic equation has a long history in such applications in biometrics (Neter and Maynes 1970). A careful examination of predictor variables and model form resulted in a mortality model that had the same general form for all species, which were modeled independently:

$$P = (1 + e^{b_0 + b_1/D + b_2 CR + b_3 BAL})^{-1} \qquad (4)$$

where P is the probability of mortality (5 year), and D, CR, and BAL are previously defined, and b_0–b_3 are maximum likelihood estimates of the parameters. All parameter estimates conform to expectations. The intercept is positive and the coefficient of D^{-1} is negative in all cases, resulting in decreasing mortality rates with increasing diameter. The coefficient of CR is positive in all cases, resulting in increasing mortality rates as crown ratio decreases. And the coefficient of BAL is negative in all cases, indicating that mortality rate will be higher as basal area in larger trees increases and a tree's competitive status is less favorable. In general, the species-specific mortality models are all well behaved and match the observed mortality rates quite well (fig. 1).

Regeneration and Ingrowth

Regeneration is such an important aspect of Austrian forest management that law requires any stand with percent crown coverage less than 33 percent to be reforested within 5 years of harvest with either natural or planted stock.

Moser (1996) developed an interim ingrowth model. In the first stage, separate logistic functions predict the probability of ingrowth (new trees with D at least 5 cm) for four mutually exclusive cases of regeneration:

1. Average tree height < 1.3 m on the plot;
2. Average tree height ≥ 1.3 m but all trees with D < 5 cm;
3. Trees with 5 cm ≤ D < 10.4 cm on the plot;
4. Trees with D ≥ 10.4 cm on the plot.

Because there is no overstory density for cases 1 and 2, the independent variables are only elevation and slope. In cases 3 and 4, the minimum inventory D of 5 cm has been reached, which allows for calculating stand density. Thus, in cases 3 and 4 the independent variables are basal area per ha, quadratic mean diameter, and CCF.

In the second stage, the number of ingrowth trees is then estimated with a logarithmic regression using elevation, soil depth, and the previously mentioned stand density variables.

In the third stage, diameter D of each ingrowth tree is drawn from a Weibull distribution, with parameters that depend allometrically on the predicted number of ingrowth trees. Finally, the species of the ingrowth is arbitrarily
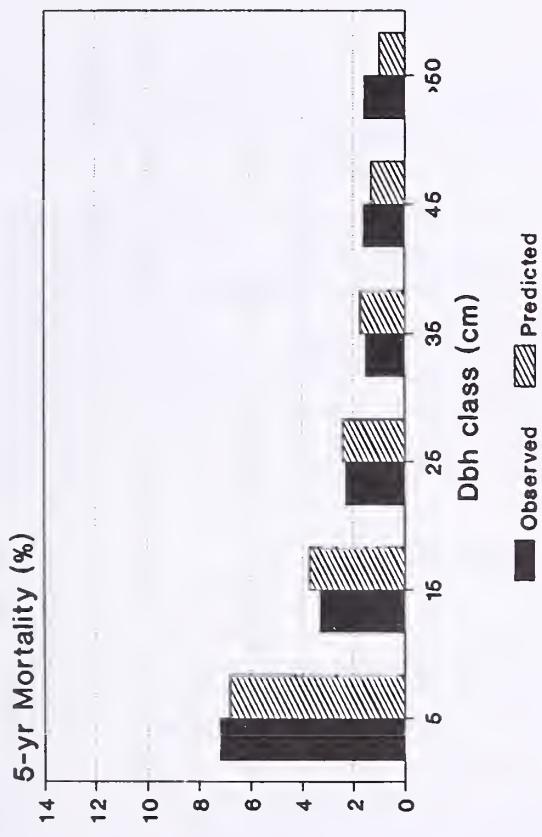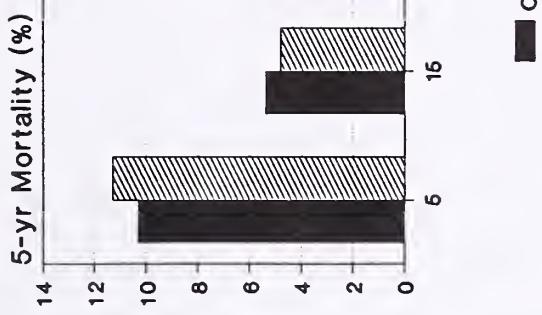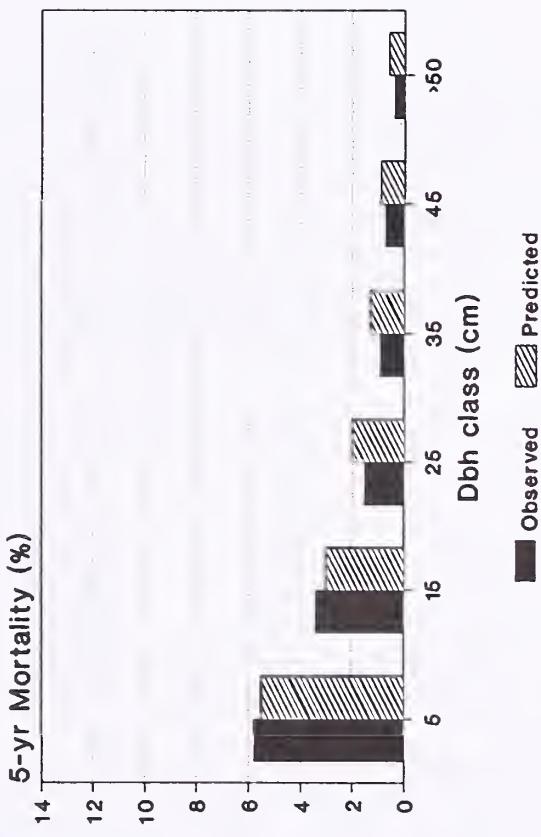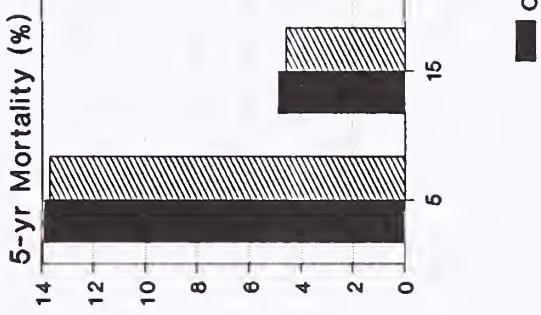
Figure 1—Observed (solid) and predicted (shaded) 5 year mortality rate versus diameter class (cm) for Norway spruce, white fir, European larch, and Scots pine.

assigned as the main species of the overstory; if there is no overstory, the main species from the next sample point in the same cluster is assigned.

The regeneration and ingrowth features of PROGNAUS are under development and will be improved as additional research is completed.

Validation

Data from an independent thinning experiment (Litschau) and not used in model development were used for validation (Sterba and Monserud 1996, 1997). Twenty-one permanent plots were remeasured from 1977 to 1992 in 5 year intervals; species composition was Norway spruce and Scots pine.

If the model is accurate and not over-fitted, the percentage of explained variation should be comparable in two representative samples from the same population. This was indeed the case, for the observed basal area increments and those projected by PROGNAUS exhibited squared correlation coefficients (r^2) for both spruce and pine that are quite close to the multiple R^2s of the original model using the Austrian National Forest Inventory data.

Predicted versus observed basal area increment for the 22 permanent plots is displayed in figure 2 for the three measurement periods. Predictions in the left three graphs use intercept determined solely from site descriptors, while predictions on the right side use an intercept determined from *BAI* in the first period according to Stage's (1973) calibration procedure. Using site descriptors alone to estimate the intercept results in a small but significant overestimation in the first period. Accurate predictions obtained with increment calibration is clearly seen in the first period, as is the increasing underestimation in the second and third periods resulting from that same first period calibration. A plot-specific adjustment of the model's intercept using past increment did not improve predictions for Norway spruce, but did improve predictions for Scots pine. Thus, important site-specific variation not captured by the Scots pine model can nevertheless be accounted for by using increment calibration.

A time trend toward increasing underestimation of increment was detected in the later growth periods of the validation data (fig. 2). This trend agrees with a frequently reported increase in site potential of Central European stands, possibly caused by changing weather conditions, nitrogen deposition, and abandoning of litter raking (Spiecker and others 1996). Schieler and Schadauer (1993) report that in the 1980's the total volume increment was about 30 percent higher for Austria than in the previous two 10 year observation periods.

We also examined the mortality model with mortality data observed for the three measurement periods on these same validation plots. The overall pattern of predicted mortality matches quite well with observed mortality for both spruce and pine. This is especially comforting because the variability in observed mortality was rather large from period to period. For spruce, the model underpredicted the mortality rate in the smallest diameter class (5 to 10 cm), and tracked all the larger *D* classes quite well. For pine, the model underpredicted the mortality rate in the three smallest diameter classes (5 to 20 cm), and tracked the remaining *D* classes reasonably well.

Additional Features

Martin Moser (Institut für Waldwachstumsforschung, Universität für Bodenkultur, Vienna) has developed a logistic model for predicting the probability of harvesting for the next 20 years. Probabilities were determined from the same Austrian National Forest Inventory dataset used to develop the growth and mortality models. Five states are recognized:

1. No harvesting
2. Random harvesting
3. Intermediate thinning
4. Single-tree selection
5. Final clear-cutting

Random harvesting is the removal of trees damaged by storms, snow, or pests (by law, landowners are required to remove dead trees immediately to prevent bark beetle outbreaks). Moser also used the inventory data to develop transition probabilities for stem quality classes and stem damage (such as bark peeling by red deer).

Building on Moser's probability of harvesting model, Markus Flach of the Forest Inventory Institute (Forstliche Bundesversuchsanstalt) in Vienna has developed a model to calculate commercial assortments (such as sawlogs and pulp) of every tree simulated by PROGNAUS. The program (available on CD-ROM) is linked to a geographic information system operating in a Windows environment. First the user defines an area on the map of Austria. Then the program predicts the amounts of probable harvests by species and by commercial assortment for the next four 5 year periods under three scenarios:

1. Harvesting behavior of forest owners remains constant
2. Harvesting probabilities increase by 25 percent
3. Harvesting probabilities increase by 33 percent.

Harvesting restrictions set by law on National Parks and fragile or high-elevation Protection Forests are honored by the program. A summary of stocking volume and increment is provided for each scenario. For comparison, only 65 percent of the growth increment is harvested in Austria.

Conclusions

Our experience in Austria is that the FVS/Prognosis paradigm is quite robust for modeling stand development in temperate forests (and most likely boreal forests as well). In addition to the large number of successful FVS applications in temperate forests in the United States and Canada (see Teck and others 1996), we found the model was easily adapted to work in Austria in a different ecosystem on a different continent, with different species, and a different forest management culture and history. Partly because of the need for the system and user interface to be both metric and in German, the PROGNAUS simulator was written from scratch and does not utilize the FVS shell. This demonstrates that the key technology in FVS is the idea, the modeling approach itself.

Site   # Increment
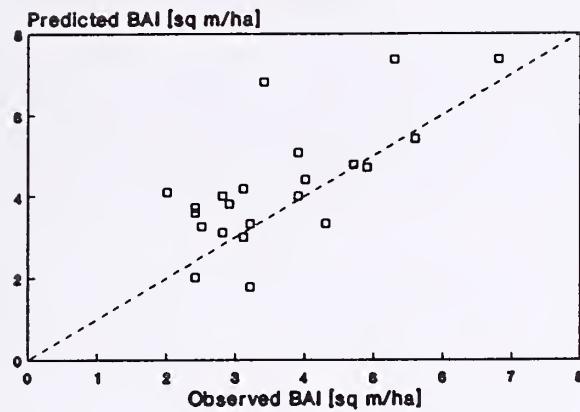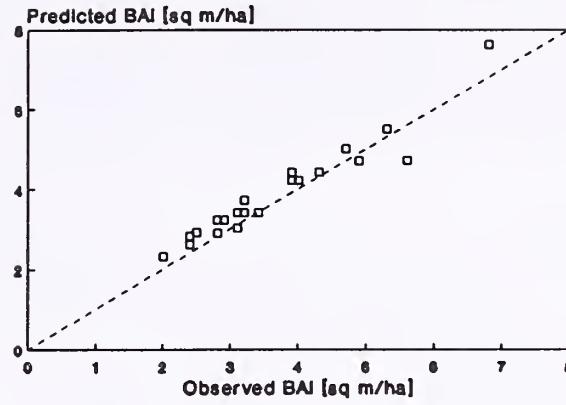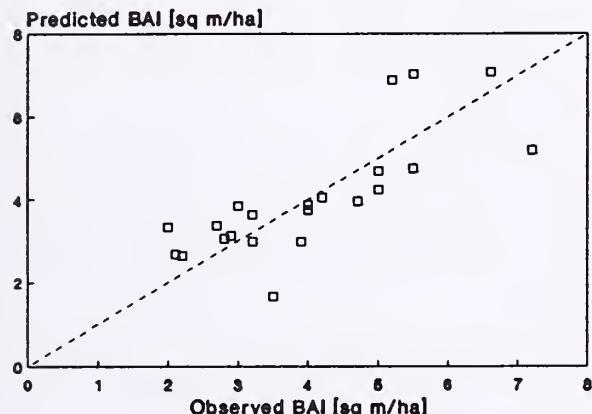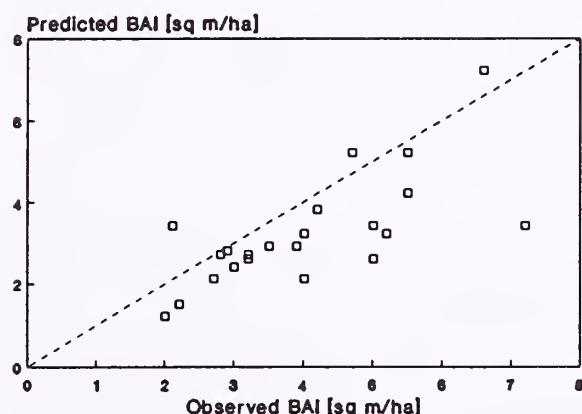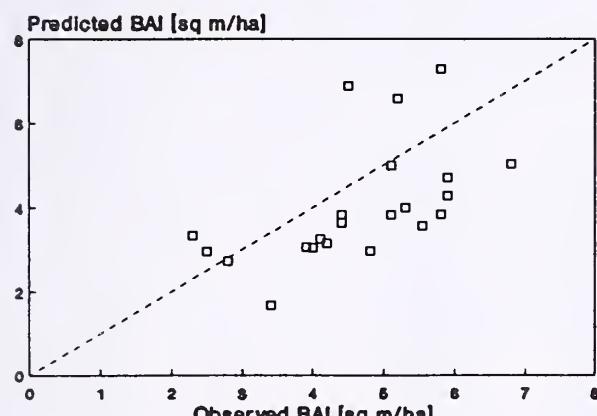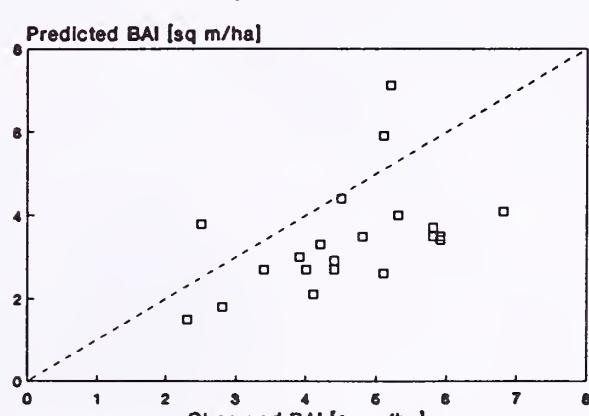
Figure 2—Predicted versus observed plot basal area increment (m² ha⁻¹) for the 22 validation plots and three remeasurement periods. Left half: Predictions use an intercept determined solely from SITE descriptors. Right half: Predictions use an intercept determined from basal area INCREMENT in the first period, according to Stage's (1973) calibration procedure.

Acknowledgments

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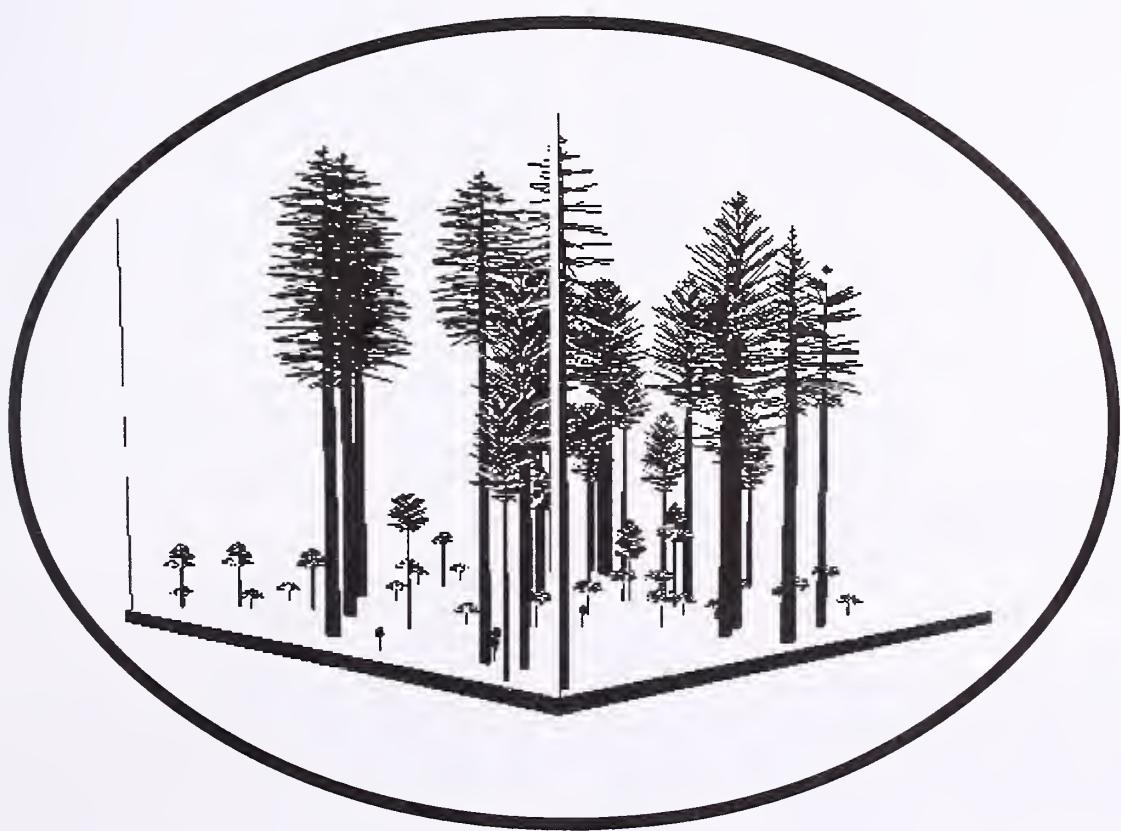
Use of the Cover Extension of Forest Vegetation Simulator and Stocking Guides to Identify Northern Spotted Owl Dispersal Habitat in Forest Communities of Central Oregon

Helen Maffei
Mike Gerdes
Scott Beyer
Roger Sandquist

Abstract—The COVER extension of Forest Vegetation Simulator (FVS) is used in conjunction with stocking guides, forest inventory data, and field observations to develop a set of procedures identifying specific central Oregon plant communities that have, as well as those that lack, the biological capability to grow sustainable northern spotted owl (*Strix occidentalis caurina*) dispersal habitat. Results demonstrate that achievement of stable spotted owl dispersal habitat is heavily influenced by site potential. For example, ponderosa pine stands with site index values greater than 90 feet can be managed to provide stable, sustainable dispersal habitat; those with lower site index values cannot. Results of the analysis were used as a basis for a Deschutes National Forest policy on dispersal habitat. The policy applies to all projects on the Deschutes that implement the President's Forest Plan.

Northern spotted owl (*Strix occidentalis caurina*) habitat may be viewed as falling into two distinct types; nesting roosting and foraging (NRF) habitat and dispersal habitat. The first type has all the structural characteristics necessary for successful reproduction. There are much more stringent structural requirements for NRF than dispersal habitat. Dispersal habitat must only have the structural characteristics necessary for owls to safely travel between NRF. These include overhead protection from predators, primarily great horned owls (*Bubo virginianus*) and northern goshawk (*Accipiter gentilis*), as well as foraging opportunities (Thomas and others 1990).

The Interagency Scientific Committee was asked to assign quantifiable stand characteristics to the above qualitative description of dispersal habitat (Thomas and others 1990). This description was released in 1990 at which time the Secretary of Agriculture established a policy that all National Forests with northern spotted owl habitat would manage consistent with the description. According to the guidelines, based on Douglas-fir communities west of the Cascade Crest, 50 percent of the potential dispersal area (by quarter township) had to have at least 40 percent canopy cover provided by trees with an average diameter (d.b.h.) of 11 inches or greater. Trees with d.b.h. averaging 11 inches or more were assumed to provide canopy high enough off the ground that the owls could fly beneath it. They were also assumed to provide standing dead and down of sufficient size to provide habitat for prey species.

Many forest specialists expressed concern regarding the biological reality of managing the drier central Oregon forest communities (within the range of the northern spotted owl) to achieve these guidelines for any reasonable period of time. Specifically, there was concern that managing to the 11-40 standard would, in many cases, result in stands that were at high risk to bark beetle attack. These attacks would make the maintenance of dispersal habitat unfeasible.

To evaluate this issue, an interdisciplinary team of wildlife biologists, entomologists, and silviculturists from the National Forests with northern spotted owl habitat, east of the Cascades as well as from the Regional Office, was formed. The members of the Eastside Dispersal Habitat Evaluation Team were: Bob Rainville, Team Leader, Deschutes National Forest; Scott Beyer, Mike Gerdes, and Jim Gray, Deschutes National Forest; Leslie Sekavec, Winema National Forest; Charlie Phillips and Monte Bickford, Wenatchee National Forest; John Nesbitt and Roger Sandquist, Regional Office.

The specific objectives of the team were:

- Develop a process for evaluating the stability or sustainability of dispersal habitat managed to 11-40.
- Pilot test the process.
- Develop a simple, nonrigorous process to evaluate, by plant community, whether some lesser cover/diameter combination than 11-40 could provide adequate dispersal habitat.

Methods

The processes developed as a result of this analysis used the Forest Inventory, stocking guides developed by Cochran (1992) for eastern and central Oregon Forests, observed

dispersal habitat in the field, and the computer model "COVER." COVER extended the capabilities of the model Forest Vegetation Simulator (formerly known as PROGNO-SIS) (Stage 1973) by modeling the development of tree crowns and, thus, predictions of canopy cover (Moeur 1985). The ponderosa pine series was chosen as the community for the pilot test because much of the expressed concern focused on the ponderosa pine forests. As a result, the following specific descriptions of the developed processes will be in terms of the ponderosa pine community.

The first step of the process was to evaluate the level of site productivity necessary to sustain 11-40 (without significant risk to bark beetle attack) for the ponderosa pine community. Different levels of canopy cover and diameter were compared to bark beetle risk for various levels of site productivity. Site productivity was represented using site index values by Barrett (1978). Bark beetle risk was projected using Cochran's (1992) stocking guide for ponderosa pine. This guide was developed from field studies in eastern and central Oregon. It could be considered a bark beetle hazard rating system, of sorts, since mortality due to mountain pine beetle (*Dendroctonus ponderosae* Hopkins) rather than suppression was found to be the primary regulator of stocking density. The Upper Stocking Level (USL) in the guide estimates the critical density, above which, mountain pine beetle mortality can become severe. This critical density differs by site potential; stands with higher site potential can carry more density before the critical density or upper stocking limit (USL) is reached than less productive stands (Cochran 1992). At stocking levels above the USL it was, therefore, assumed that the stand was unstable and could not sustain itself at that level of density over time.

Canopy cover and diameter comparisons were made using simplified ponderosa pine stands. Within each of these "simplified" stands, every tree was assumed to be identical, having the same diameter and same canopy width. Canopy

widths, by diameter class, were estimated using average measurements from the 1985 Deschutes National Forest Vegetative Resource Survey. The simplified stands were used instead of "real" stands to focus the comparison by minimizing the number of variables.

The next step in the analysis process was to evaluate whether 11-40 was essential for the successful dispersal of northern spotted owls east of the Cascade Crest or whether some lesser d.b.h. to cover ratio would be sufficient. A range of field conditions that were, and were not, being used as successful dispersal habitat in even-aged ponderosa pine stands were evaluated. Plots were taken in these stands and estimates of cover were computed from the plot information using the COVER extension of Forest Vegetation Simulator (Moeur 1985). From these field observations and measurements, minimal d.b.h./cover combinations for suitable dispersal habitat were identified. Suitable combinations were then compared to the USL (Cochran 1992).

At the time this analysis was done, the COVER model estimated crown width using equations developed in the Northern Rocky Mountains (Moeur 1981). The team wanted to make sure these relationships were not significantly different from those in central Oregon. The correspondence between the crown widths projected in the COVER model and local stands was informally evaluated. A limited comparison was made between the widths measured in the Deschutes VRS and those projected in the COVER model.

Results and Discussion _____

Comparisons using the simplified ponderosa pine stands show, for stands with site indices under 90 feet (Barrett 1978), the 11-40 d.b.h. to cover ratio cannot be attained at, or below, the upper stocking level (USL) (fig. 1). This is good evidence that 11-40 cannot be sustained in these less productive stands over a reasonable period of time because it is
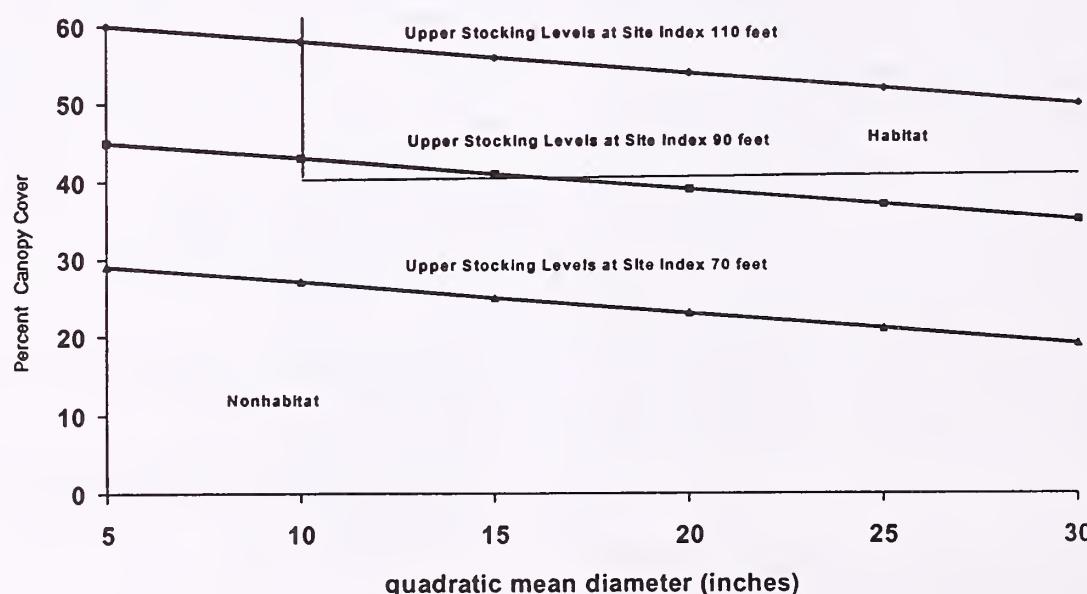
Figure 1—Comparison of northern spotted owl dispersal habitat in even-aged ponderosa pine with upper stocking levels at three site indices. Dispersal habitat was defined by the Interagency Scientific Committee (Thomas and others 1990) as 40 percent canopy cover provided by trees with a minimum average diameter of 11 inches.

highly likely that bark beetle attack will result in a reduction in canopy cover to levels that correspond to the USL, or lower. Further, even-aged ponderosa stands at site index 90 feet may not be able to both sustain 11-40 and remain at low risk to bark beetles (fig. 1) as the trees mature because as individual trees increase in diameter, the amount of cover provided per unit of basal area steadily declines. Thus, we should not expect to sustain 11-40 as these stands mature.

Results obtained using field observations indicate that something less than 11-40 will provide suitable dispersal habitat (fig. 2). Dispersal habitat can be provided by even-aged ponderosa pine stands with as little as 35 percent cover and quadratic mean diameter as small as 8 inches.

There appeared to be good correspondence between ponderosa pine crown widths projected by the inventory data and those projected by the COVER model. This correspondence provided evidence that projection of ponderosa pine canopy cover by the model could be used without having to adjust for local conditions. This is not an issue at present, however. The model has since been adjusted, by variant, to incorporate local canopy with relationships using the recently completed 1996 Continuous Vegetation Survey (CVS).

The results of the analysis were used in 1996 to develop a Deschutes National Forest policy on dispersal habitat (Collins 1996). This policy applied to all projects implementing the President's Forest Plan. Given a specific stand that could serve as part of a connective corridor between nesting, roosting, and foraging areas, the stand will be managed at 11-40, or above, provided stocking levels remain below the upper stocking level (USL) or some other appropriate measure of stand stability or sustainability. If this is not possible to achieve given the potential of the site then the local analysis procedure we have outlined in this paper will provide the basis for determining whether or not the stand can provide dispersal habitat over a reasonable period of time. If the site in question does not have the capability to provide sustainable habitat, then the stand will not be considered a candidate for dispersal habitat and will not be managed as such.

How might the COVER model's capability be improved for this type of application? The present model assumes no crown overlap. We know, however, that this overlap exists more often than not in many forest communities. Estimates, therefore, derived using this procedure were probably optimistic in term of the actual cover potential for a given site, especially if the considered plant community tends to have grouped vegetation (fig. 3). An example of the inherent variation in grouping that we might encounter in central Oregon, the density, by stand exam point, of a typical ponderosa pine stand with a site index value of 93 feet is displayed in figure 4. We are looking forward to the new feature "PERCOVE" (currently under development) of the COVER Model. PERCOVE will have the capability of incorporating crown overlap into cover projections. When this feature becomes available we plan to use it to adjust our projections of canopy cover capability for a given site.

Conclusions

Results demonstrate that achievement of stable northern spotted owl dispersal habitat in central Oregon plant communities is heavily influenced by site potential. We believe that the analysis and developed processes have helped us to better evaluate the potential for various plant communities to sustain northern spotted owl dispersal habitat as described by the Interagency Scientific Committee. It has also enabled us to refine their definition of dispersal habitat to better reflect the local forest conditions and habitat requirements of central Oregon. This general procedure could be modified and used to evaluate the sustainability of other types of wildlife habitat. It also could be used as a relatively simple procedure to develop interim local descriptions of
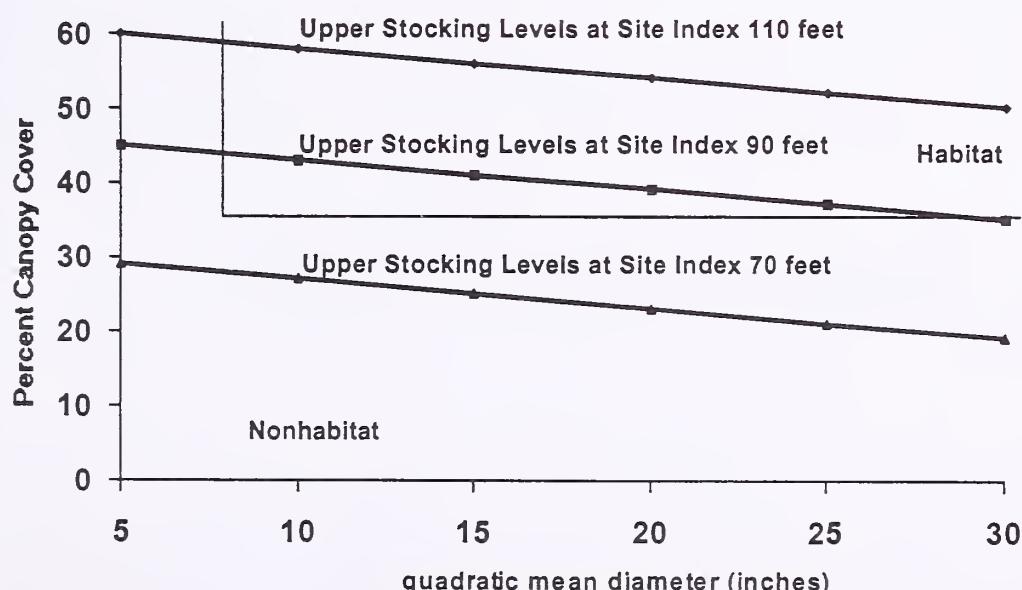
Figure 2—Comparison of northern spotted owl dispersal habitat with upper stocking levels at three site indices. Dispersal habitat was defined by local field observations as 35 percent canopy cover provided by trees with a minimum average diameter of 8 inches.
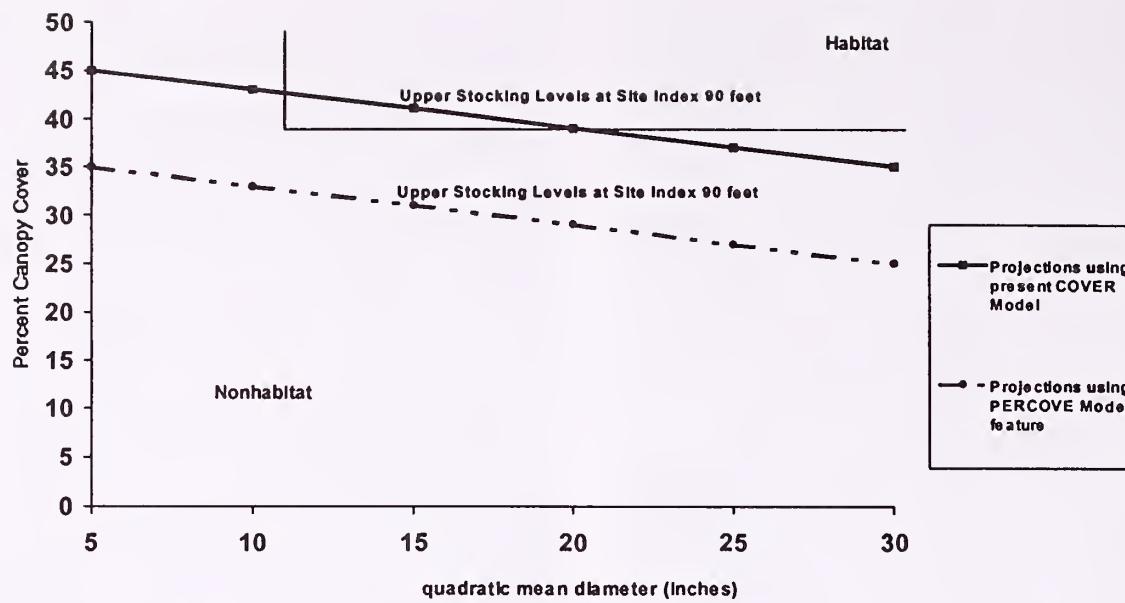
Figure 3—Hypothetical difference in the relationship between northern spotted owl dispersal habitat and upper stocking levels using the present COVER model versus the new feature of the COVER model "PERCOVE" in ponderosa pine stands with significant canopy overlap. PERCOVE will give the COVER model the capability to incorporate canopy overlap into cover projections.
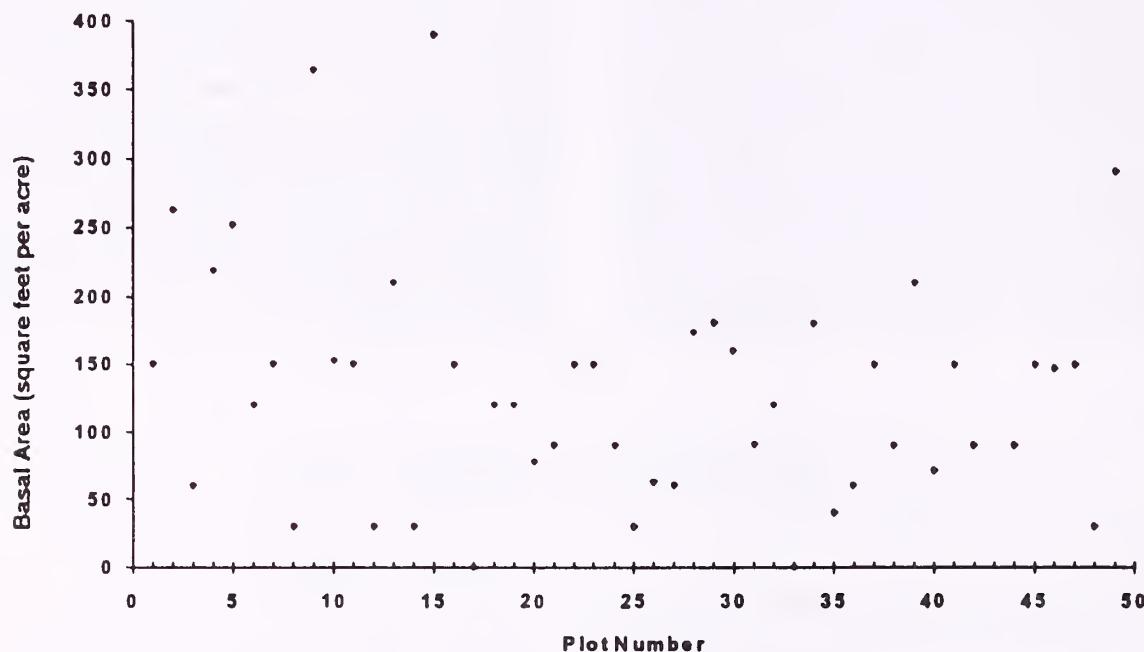
Figure 4—Basal area by stand exam plot for a typical even-aged ponderosa pine stand in central Oregon (109 acres). This figure illustrates the extremely high variability in density that often exists in individual stands in central Oregon forest communities.

habitat while land managers are waiting for results of more rigorous long term scientific research on habitat requirements.

It should also be stressed that it was important to the success of the project, as well as to potential future wildlife applications, that Forest Vegetation Simulator had the capability to make projections in terms of interest to wildlife biologists. As quantitative descriptions, suitable habitat, insect-, disease-, and fire-hazard rating systems improve, FVS should be an even more powerful and useful tool for wildlife application in the future.

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The Use of the Forest Vegetation Simulator for the California Spotted Owl Environmental Impact Statement

Larry Wilson

Abstract—The Cal Owl EIS (release of revised draft pending) was a bioregional planning effort encompassing 10 National Forests containing approximately 7 million acres. FVS was used to generate Spectrum compatible yield tables and age-dependent tables depicting projected changes in volume, cover, and a number of habitat elements over the course of 300 years under a variety of stand management prescriptions. Growth projections were performed on a PC using the WESSIN and SORNEC FVS variants, executed from within a Windows 3.1 shell program (FVSWIN) that was developed for the project.

The California Spotted Owl Environmental Impact Statement (U.S. Department of Agriculture, Forest Service, Pacific Southwest Region 1996) was initiated in January 1993 to develop a long-term strategy to maintain the viability of the California spotted owl on National Forest lands within the Sierra Nevada province. The area under consideration included nine National Forests plus the Lake Tahoe Basin Management Unit, an area covering over 7 million acres.

In accordance with normal NEPA procedures, a set of objectives, and a set of alternative management strategies were developed and evaluated. The four stated objectives for this EIS are:

A. Provide key California spotted owl habitat elements by:
  1. Protecting known owl next stands from significant modification.
  2. Protecting very large old trees in those timber strata that will provide suitable habitat.
  3. Reducing the likelihood of high-severity fires.
B. Contribute to the viability of other widely distributed plant, wildlife, and fish species whose populations may be at risk.
C. Contribute to the economic and social well-being of local communities and the Nation.
D. Provide for sustainable levels of renewable natural resources consistent with multiple-use objectives.

A key feature of this project was its "ecosystem approach." With respect to growth and yield modeling, this meant tracking both commodity outputs and habitat elements.

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Analysis of alternatives was done using Spectrum (U.S. Department of Agriculture, Forest Service 1995), the successor to FORPLAN. My job was to generate Spectrum compatible tables of projected yields and effects over the planning horizon for the various vegetation management treatment options under consideration using the Forest Vegetation Simulator, FVS (Teck and others 1996). A Windows 3.1 "shell" program, FVSWIN was developed to aid in this task.

Model Output

Forest growth and yield data generated by FVS projections are passed to Spectrum as specially formatted ASCII text files (fig. 1, 2). Stand conditions and output levels are updated each time period, which for this project was once per decade. Codes that identify the analysis area and treatment type must also be included in the Spectrum yield tables. Analysis areas were forest vegetation strata from the most current National Forest inventories. Treatment types were special codes that identified the various silvicultural treatments under consideration.

The following data were incorporated into multi-product/multi-stand age dependent yield tables (stand level statistics on a per acre basis):

MBF— Merchantable board feet (Scribner), thousands, net
PINE — Merchantable board feet of pine species, thousands, net
CCF — Merchantable cubic feet, hundreds, net
SRI — Stand Resiliency Index, an index of a stand's susceptibility to stand replacement fire, higher values = higher susceptibility. $SRI = 1 + \log(tpa1/qmd)$
CHIP — Dry tons per acre of submerchantable material
\# > 30 — Number of trees per acre ≥ 30 inches d.b.h.
\# > 40 — Number of trees per acre ≥ 40 inches d.b.h.
SNAG — Number of snags per acre ≥ 30 inches d.b.h.
V < 30 — Board foot volume of trees < 30 inches d.b.h., net

CWHR, a vegetation seral stage classification system, and a spotted owl habitat suitability index were also calculated and incorporated into age dependent tables (Mayer and Laudenslayer 1988).

The multi-product yield table shown in figure 1 is relatively straightforward. Levels for the various outputs are updated for each decade, reading from left to right. Harvest levels are shown in a similar manner. "A21" indicates a starting age of 210, the standard for nonplantation strata. Interpretation of the CWHR age dependent table (fig. 2) is more difficult. The line beginning with "#5 21 21" contains a

```
*I              9C3G
*A EXIST    21 M3G  STRD        WS   03-30-1997      18:31:08  Cycles:    5
  MBF-!A21 31.30  37.95  43.56  49.05  54.03
  MBF-!S21  4.41   4.96   5.23   4.96   4.79
  SRI-!A21  4.41   4.96   5.23   4.96   4.79
  PINE!A21 15.63  18.23  20.41  22.14  23.86
  CCF-!A21 53.74  65.33  74.97  84.69  93.46
  CHIP!A21 12.31  13.43  14.60  14.63  15.07
  #>30!A21  7.90  10.55  12.31  14.70  16.34
  #>40!A21  1.82   2.11   2.89   3.69   4.07
  SNAG!A21  1.18   0.62   0.59   0.92   1.46
  V<30!A21 17.08  19.28  21.08  21.75  22.47
```

Figure 1—Spectrum formatted multi-product yield table from a 5 cycle FVSWIN run.

```
#3              9C3G                                                    M3G-STRD
#4
#5  21 21                                         1.0
#5  22 25                                                      1.0
```

Figure 2—Spectrum formatted age dependent table for CWHR classification
from a 5 cycle FVSWIN run.

1.0 in field 4, the line beginning with "#5 22 25" contains a 1.0 in field 5. Field 4 corresponds to CWHR class 5M, field 5 to CWHR class 6. The interpretation of these 2 lines is the initial CWHR classification is 5M, in decades 2 through 5, the CWHR classification is 6. Whenever the CWHR class changes from one decade to the next, a new line is printed, showing the growth decades during which the new classification is maintained.

The data in these tables were produced by computer post-processor routines that gather and process data from the FVS TREELIST output files. These routines were integrated into FVSWIN, so that the tables were automatically created for each FVS run. After FVS simulations for all vegetation strata-silvicultural prescription combinations for a particular forest were done, an additional processing step combines the individual yield tables into multi-stand yield tables used by Spectrum. Additional formatting features and Spectrum codes are added during this process.

Design Elements

Some of the characteristics of the project that were considered in the design of FVSWIN included:

- Long timeframe
- Complex prescriptions
- Multiple forests
- Project habitat elements as well as commodities
- Build yield streams for spectrum analysis
- Anticipate changes and reruns

These characteristics implied some obvious and some not-so-obvious modeling features. Multiple forests necessitated

running both the SORNEC (Dixon 1992) and WESSIN (Dixon 1994) variants, therefore it was necessary to maintain duplicate keyword files containing variant specific references to species identity. Long-term sustained yield analysis required that projections be run for 300 years. This necessitates providing for ingrowth, in order for the projections to be more "realistic". Ignoring ingrowth is equivalent to modeling complete suppression of ingrowth, which, for the prescriptions modeled, was not the intent. If commodity outputs, such as volume per acre, were the only variable under investigation, ignoring ingrowth may be acceptable for modeling short term even-aged management scenarios, as the effect of the understory vegetation on volume growth could be ignored. However, for the California Wildlife Habitat Relationships classification system, understory canopy cover is an important factor, and ignoring it would bias the results.

In order to be able to (relatively) quickly rerun a forest, or the entire set of 10 forests, a number of automation features were included. For example, the plantation commercial thinning prescription called for reducing stocking to 70 percent of normal in any cycle where stocking has risen to over 90 percent of normal (similar to the THINAUTO implementation). Normal stocking was determined from normal yield tables for pine types, mixed conifer, and red fir published by Meyer (1938), Dunning and Reineke (1933), and Schumacher (1928), respectively. FVSWIN was set up to read the site-class specific values according to the vegetation type automatically, utilizing a technique described in this paper. Logic was also included that inserted the appropriate analysis area and treatment codes used by Spectrum into the yield files.

FVSWIN Architecture

FVSWIN was designed to be a FVS-projection-build-and launch application with integrated post-processors, running at the vegetation stratum level. To initiate a run, the user:

- Sets run parameters such as projection length (number of cycles), common year, forest, year for first allowed harvest, minimum harvest amounts, ingrowth specifications, and so forth, using Windows 3.1 controls such as dialog boxes, list boxes, and text boxes.
- Selects one or more strata from a list box showing the strata for the forest under consideration.
- Selects one or more silvicultural prescriptions, identified by a four character prescription code, from a list box.
- Selects "Go" from the menu bar.

The program then builds and executes FVS runs, including post-processors for each selected stratum/prescription combination, running in the "background" of the Windows multi-tasking environment. Output files are automatically saved in a user-selected directory. No additional input is required.

For each run, FVSWIN writes a command keyword file, named dummy.cmd, based on the settings and prescription being run, copies the tree data file to a file named dummy.tre, and executes FVS as a child process using the WinExec (Windows 3.1 API) function, specifying "dummy.cmd", "dummy.tre", "dummy.out", "dummy.trl", "dummy.sum", and "dummy.ch" as the command line arguments. When FVS terminates, the selected post-processor programs are run to generate the Spectrum tables and other outputs, using data in the FVS treelist output files. When the post-processors are finished, the program runs the next stratum/prescription combination.

Keywords are added to the dummy.cmd file either directly from FVSWIN or indirectly, via a mechanism similar to ADDKEYS. For example, if 20 is entered in the "Number of Cycles" text box, "NUMCYCLE 20" will be written in the dummy.cmd file. If the Forest selection is "Eldorado", the file "WS_SOSI.CTL" will be automatically added to the dummy.cmd file. This file is a control file containing merchantability specifications, a set of MCFDLN and BFFDLN keywords (log-linear form and defect corrections), and so forth.

To simulate a given silvicultural prescription, the user selects from a list of prescriptions in a list box showing all files with an ".RX" suffix. The RX files contain a MGMTID keyword/supplement set to identify the prescription and pointers to one or more other files that contain the activity keywords. The prescription simulation keyword sets are built by assembling keyword file fragments. FVSWIN contains logic for determining which keyword file fragments to include, based on entries in the .RX file. Figure 3 displays an RX file for the plantation commercial thinning prescription, CT_2. The first line has the MGMTID keyword/supplementary data information. The second line tells FVSWIN to add a file with a ".CTT" suffix whose prefix is made up of the veg type and site class, for example, M1.CTT, if the stratum being run is a mixed conifer type and site class 1. EXTVEGSC is a FVSWIN keyword specifying an external file referenced

```
MGMTID CT_2
EXTVEGSC CTT
CUT CT_2
```

Figure 3—An FVSWIN "RX" File, CT_2.RX.

by vegetation type and site class, with the suffix indicated in field 2. The ".CTT" file contains the commercial thin density targets, specific to a given vegetation type and site class (fig. 4). The third line of the .RX file, "CUT CT_2" instructs FVSWIN to add the file CT_2.CUT" (fig. 5), that contains the keywords that implement the cutting treatment, using the variables MAXBA and MINBA that are defined in the ".CTT" file: Creating sets of FVS keyword files to perform specific functions allows for modularization, resulting in fewer and smaller keyword files that need to be developed. The commercial thinning targets in the .CTT files are used in several .CUT files. Other FVSWIN keywords used in .RX files include EXTVARVEG and PLANT. EXTVARVEG is used to add keyword files referenced by variant and vegetation type. PLANT (FVSWIN keyword) is used to add ESTAB keywords for prescriptions that include planting.

Ingrowth Modeling

Since neither the WESSIN nor SORNEC variants, used for this project, include the capability to predict natural regeneration, a system for doing so was incorporated into FVSWIN. The basic approach was to allow for setting ingrowth parameters via dialog boxes, and then translate the settings into ESTAB keywords, which were incorporated into the dummy.cmd file. The three main elements of the ingrowth sub-model were the "trigger," setting the number of seedlings, and the species distribution.

Four triggering mechanisms were developed: (1) fixed interval, (2) probability function, (3) decline in CCF, and (4) post-treatment. Year of earliest first regeneration pulse and minimum repeat time were other aspects of the triggering mechanism.

Three means for setting the number of seedlings were provided: (1) fixed number, (2) random within a set range, and (3) linear function of CCF, with a user defined maximum corresponding to CCF = 0.

Four methods for determining the species composition (percent of number of seedings, by species) were developed: (1) set proportions, (2) same species composition as used for "bare ground" runs, (3) proportional to overstory basal area, and (4) tolerance weighted proportions (proportional to overstory basal area, with an adjustment for relative shade tolerance. Average seedling height could also be set via a text box.

Figure 6 displays the keyword routine corresponding to the following settings:

- Trigger—12 percent probability
- Number—Fixed, 170
- Species distribution—proportional to basal area
- Earliest first pulse—2026
- Minimum Repeat Time—40 years
- Seedling Height—1.5 feet

```
COMMENT
        FILE: M1.CTT
                Commercial thinning basal area targets, "M" type
                Site class 1.
                BA targets set by age.
                MAXBA and MINBA values are 90% and 70% of normal
                basal area from Dunning & Reineke Bull. 354,
                        Site index 70.
END
IF                  149
AGE LT 35
THEN
COMPUTE             0
MAXBA = 140
MINBA = 109
END
ENDIF
IF                  149
AGE GE 35 AND AGE LT 45
THEN
COMPUTE             0
MAXBA = 187
MINBA = 146
END
ENDIF
~~additional basal area targets for each 10-year age class~~
IF                  149
AGE GE 145
THEN
COMPUTE             0
MAXBA = 315
MINBA = 245
END
ENDIF
```

Figure 4—Part of an FVSWIN "CTT" file, M1.CTT.

```
COMMENT
        FILE: CT_2.CUT
                Commercial thinning regime 2
                When basal area reaches MAXBA, stand is thinned
                to MINBA
                MAXBA and MINBA values are Veg Type and Site Code specific
                targets at current stand age, contained in ".CTT" files.
                They are added automatically by FVSWIN.
END
IF                  19
BBA GE MAXBA
THEN
THINDBH             0   PARMS(4,999,1,0,0,MINBA)
THINDBH             0   PARMS(0,4,1,0,40,0)
ENDIF
```

Figure 5—An FVSWIN "CUT" file, CT_2.CUT.

```
IF                  40
YEAR GE 2026 AND &
RANN LE 0.12
THEN
COMPUTE             0
IGBNUM = 170
END
ESTAB               3
NATURAL             3    PARMS(1,&
IGBNUM * (SPMCDBH(2,1,0)/SPMCDBH(2,0,0)),100,3,1.5,2)
NATURAL             3    PARMS(2,&
IGBNUM * (SPMCDBH(2,2,0)/SPMCDBH(2,0,0)),100,3,1.5,2)
NATURAL             3    PARMS(3,&
IGBNUM * (SPMCDBH(2,3,0)/SPMCDBH(2,0,0)),100,3,1.5,2)
NATURAL             3    PARMS(4,&
IGBNUM * (SPMCDBH(2,4,0)/SPMCDBH(2,0,0)),100,3,1.5,2)
NATURAL             3    PARMS(5,&
IGBNUM * (SPMCDBH(2,5,0)/SPMCDBH(2,0,0)),100,3,1.5,2)
NATURAL             3    PARMS(6,&
IGBNUM * (SPMCDBH(2,6,0)/SPMCDBH(2,0,0)),100,3,1.5,2)
NATURAL             3    PARMS(7,&
IGBNUM * (SPMCDBH(2,7,0)/SPMCDBH(2,0,0)),100,3,1.5,2)
NATURAL             3    PARMS(8,&
IGBNUM * (SPMCDBH(2,8,0)/SPMCDBH(2,0,0)),100,3,1.5,2)
NATURAL             3    PARMS(9,&
IGBNUM * (SPMCDBH(2,9,0)/SPMCDBH(2,0,0)),100,3,1.5,2)
NATURAL             3    PARMS(10,&
IGBNUM * (SPMCDBH(2,10,0)/SPMCDBH(2,0,0)),100,3,1.5,2)
NATURAL             3    PARMS(11,&
IGBNUM * (SPMCDBH(2,11,0)/SPMCDBH(2,0,0)),100,3,1.5,2)
TALLYONE            3
END
ENDIF
```

Figure 6—Example ESTAB keyword routine for
simulating background ingrowth.

Group Selection

A special processing mode was developed to simulate
group selection management. Group selection areas were
modeled as two separate FVS runs, one for the matrix (such
as a veg stratum), the other for the regeneration groups.
Regeneration groups were modeled as "bare ground" FVS
runs, using the site information (site class, elevation, and so
forth) from the matrix, and a 15 percent reduction of small
tree height growth (REGHMULT = .85) to account for
competition effects (this could be varied according to the size
of the regeneration opening). Matrix and regen runs could
use various treatment prescriptions.

A conversion period was defined, 200 years for this project,
during which time the matrix stand was gradually replaced
with regeneration groups. Outputs (board feet, CWHR, and
so forth) were calculated based on a "stand" which was a
weighted composite of the matrix and one or more regenera-
tion groups. For example, in the first cycle of the conversion
period the composite stand consists of 95 percent matrix
(cycle 1) and 5 percent bare ground. The cycle 2 composite
stand is 90 percent matrix (cycle 2), 5 percent bare ground,
and 5 percent 10 year old stand. At the end of the conversion
period, the composite stand is made up of 5 percent of each
age class (cycle) of the regeneration run. For the purpose of
calculating outputs and habitat elements, the group selec-
tion area is considered a single, composite stand.

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Vegetation Projection and Analysis of the Cumulative Effects of Timber Harvest

Helge Eng

Abstract—This study analyzed the potential cumulative impacts of timber harvest on habitat suitability and connectivity of late successional forest in northwestern California. The growth and yield model FVS was used with remotely sensed vegetation coverages to simulate forest structure development over time in response to timber management activities. Analysis of fragmentation of late successional forest was based on spatially referenced vegetation coverages. Harvesting 100 acres did not significantly affect connectivity of late successional forest or habitat quality for the Pacific Fisher. The results may be different in species with a smaller home range than the Pacific Fisher. Limiting harvest in riparian areas and northern spotted owl activity centers had only a marginal mitigation value for connectivity of late successional forest in a large landscape (100,000 acres) context.

California's forest practice rules require landowners to prepare timber harvest plans for areas they intend to harvest. These plans must be approved by State government agencies before timber harvest can commence. As part of the timber harvest plan, the landowner must show that no significant cumulative impacts will result from proposed timber harvesting operations.

The cumulative impacts analysis described here originated in a 99 acre timber harvest plan for an area that contained late successional forest and potential habitat for sensitive species, notably the Pacific Fisher. The Department of Forestry and Fire Protection, with other State agencies, undertook an independent analysis of the potential cumulative impacts of the planned harvest operations.

The study focused on a large landscape level analysis of connectivity of late successional forest and habitat suitability for the Pacific Fisher. An area of 100,000 acres was deemed sufficiently large to support a local population of Pacific Fishers. Furthermore, 100,000 acres or larger was considered an adequate assessment area for evaluating cumulative effects on a community of potentially interbreeding individuals. This assessment area was set up by drawing a 100,000 acre circle around the proposed timber harvest plans.

The California Wildlife Habitat Relationships (CWHR) vegetation classification system (Mayer and Laudenslayer 1988) was used as the vegetation typing system to describe forest structure and habitat connectivity. The CWHR vegetation classification system is similar to most traditional forest typing systems. The species, size, and density parameters used in this study are shown in Table 1.

Projection of Forest Structure

A remotely sensed vegetation coverage and forest inventory plots were used to describe current forest structure. The Forest Vegetation Simulator (FVS) (Teck and others 1996) growth and yield model was used to develop yield streams and forest development trajectories from the inventory plots. The forest development trajectories were then mapped to the vegetation coverage. Forest structure projection thus became a four-stage process:

1. All inventory plots were assigned to a CWHR class by translating individual tree records into an overall stand structure class.
2. The tree records from all the plots assigned to the same CWHR class were grouped together and their growth projected over time using the FVS growth and yield model.
3. Projected yield streams were translated into CWHR forest development trajectories. One such trajectory was developed for each unique CWHR category in the vegetation coverage describing current conditions. This process resulted in the CWHR growth table shown in table 2.

Table 1—The California Wildlife Habitat Relationships classification system.

Type:

Aggregated type	CWHR type classes
Mixed Conifer	Douglas-fir, Jeffrey pine, Klamath mixed conifer, Ponderosa pine, Redwood.
Conifer/Hardwood	Montane hardwood-conifer, Montane hardwood.
Non-forest	Shrub, Barren, Water, Urban.

Size:

WHR Symbol	WHR size class	D.b.h., inches
1	Seedlings	<1.0
2	Saplings	1.0 - 5.9
3	Pole trees	6.0 - 10.9
4	Small trees	11.0 - 23.9
5	Medium/large trees	>24.0
6	Multi-layered	Size class 5 trees over a distinct layer of size class 4 or 3 trees, total cc >60 percent

Canopy closure:

CWHR Symbol	CWHR canopy Closure class	Percent cover
S	Sparse	10.0 - 24.9
P	Open	25.0 - 39.9
M	Moderate	40.0 - 59.9
D	Dense	60.0 - 100.0

4. Table 2 was used as a lookup table keyed to the CWHR class of each polygon in the vegetation coverage describing current conditions. Assigning a trajectory of forest type development for each polygon in the vegetation coverage of current conditions resulted in a set of projected vegetation coverages over time. It was possible to evaluate the connectivity of late successional habitat in the projected vegetation coverages because all the coverages were spatially referenced.

Initial Forest Structure

Satellite imagery classified to CWHR classes was used as the basic vegetation coverage describing current forest structure on the assessment area (Wheeler and others 1993). Because most of the wildlife species in the area respond more to forest structure than to species composition, the analysis did not require tracking each CWHR habitat type over time. Consequently, as detailed in table 1, CWHR habitat types were aggregated into three broad classes, mixed conifer, conifer/hardwood, or nonforest. The overall classification accuracy of these aggregate categories was 84 percent. The classification accuracy of size and canopy

Table 2—Projected CWHR forest structure for 50 years.

1993	1998	2003	2013	2023	2033	2043
NF	NF	NF	NF	NF	NF	NF
MC2D	MC2D	MC2D	MC4D	MC4D	MC4D	MC6
MC2M	MC2D	MC2D	MC4D	MC4D	MC4D	MC6
MC2P	MC2D	MC2D	MC4D	MC4D	MC4D	MC6
MC2S	MC2D	MC2D	MC4D	MC4D	MC4D	MC6
MC3D	MC3D	MC4D	MC4D	MC4D	MC4D	MC6
MC3M	MC3D	MC4D	MC4D	MC4D	MC4D	MC6
MC3P	MC3D	MC4D	MC4D	MC4D	MC4D	MC6
MC3S	MC3D	MC4D	MC4D	MC4D	MC4D	MC6
MC4D	MC4D	MC4D	MC6	MC6	MC6	MC6
MC4M	MC4D	MC4D	MC6	MC6	MC6	MC6
MC4P	MC4D	MC4D	MC6	MC6	MC6	MC6
MC4S	MC4D	MC4D	MC6	MC6	MC6	MC6
MC5D	MC5D	MC5D	MC5D	MC5D	MC5D	MC6
MC5M	MC5M	MC5M	MC5M	MC5D	MC5D	MC5D
MC5P	MC5P	MC5P	MC5P	MC5P	MC5M	MC5M
MC5S	MC5S	MC5S	MC5S	MC5S	MC5S	MC5P
MC6	MC6	MC6	MC6	MC6	MC6	MC6
CH2D	CH2D	CH2D	CH4D	CH4D	CH4D	CH4D
CH2M	CH2D	CH2D	CH4D	CH4D	CH4D	CH4D
CH2P	CH3P	MC3M	MC4D	MC4D	MC6	MC6
CH2S	CH2P	CH3P	CH4M	MC4M	MC4D	MC4D
CH3D	CH3D	CH3D	CH4D	CH4D	CH4D	CH4D
CH3M	CH3M	CH3M	MC4D	MC4D	MC4D	MC6
CH3P	CH3P	CH3M	CH4M	CH4D	CH4D	CH6
CH3S	CH3S	CH3S	CH4P	CH4P	CH4M	CH4M
CH4D	CH4D	CH4D	CH4D	CH6	CH6	CH6
CH4M	CH4M	CH4M	CH4M	MC5D	MC6	MC5D
CH4P	CH4M	CH4M	CH4M	MC5D	MC6	MC5D
CH4S	CH4S	CH4S	CH4S	CH4S	CH5S	CH5S
CH5D	CH5D	CH5D	CH5D	CH5D	CH5D	CH6
CH5M	CH5M	CH5M	CH5M	CH5D	CH5D	CH5D
CH5P	CH5P	CH5P	CH5P	CH5P	CH5M	CH5M
CH5S	CH5S	CH5S	CH5S	CH5S	CH5S	CH5P
CH6	CH6	CH6	CH6	CH6	CH6	CH6

classes was unchanged and is documented in Wheeler and others (1993).

Estimating Forest Structure from Inventory Plots

Inventory plots consisted of Forest Inventory and Analysis (FIA) plots from Del Norte, Humboldt, and Mendocino Counties (Bolsinger 1980). The following decision rules were used to estimate CWHR type, size, and density classes from inventory plot tree lists:

Density—Maximum crown-width equations were used to predict cross-sectional crown area for individual trees (Hann and Paine 1982; Smith 1966; Warbington and Levitan 1992). Adding the crown areas for all the trees on a plot and expanding to a per-acre basis provided an estimate of canopy closure for a stand. No correction was applied for overlapping crowns. As a result, estimated canopy closure sometimes exceeded 100 percent. The CWHR density class boundaries occur at canopy closures of 60, 40, and 25 percent. At these lower canopy closure percentages, the lack of recognition of crown area overlap constitutes little bias. CWHR canopy closure class was determined by allocating the total percent canopy closure per acre for each plot into the CWHR categories in table 1.

Size Class—CWHR size class was estimated by allocating individual trees to the diameter breast high (d.b.h.) classes in table 1 and adding the cross-sectional crown areas for all the trees in each d.b.h. class. This resulted in a distribution of total stand canopy closure by d.b.h. class for each plot. CWHR size class was then determined according to the decision rules described in table 3. This canopy layer approach, in which the size class is that with the greatest percentage of overall stand canopy closure, was deemed suitable for this study in which vegetation coverages were developed from satellite imagery.

Type—Inventory plots were classified into standard CWHR type classes using the decision rules described in Barrett and others (1993). Individual species classifications were then aggregated into the categories shown in table 1.

Projecting Tree Growth and Forest Structure Development Over Time

All inventory plots assigned to the same CWHR class were grouped together for growth projection. The maximum number of inventory plots in a single CWHR class was 26; the minimum number of plots was one. The Klamath Mountains variant of FVS (Johnson 1990) was used for growth projection. Growth was projected in 5 year intervals for 50 years after harvest. No other management was modeled in this period. The same algorithm used to estimate CWHR classes from inventory plot tree lists was used to estimate projected CWHR classes from projected tree lists produced by FVS.

Management Situation

Two management situations were modeled. In the first situation, all privately owned late successional forest on the

Table 3—Decision rules for CWHR size class.

```
IF (CC < 0.05) THEN
    SIZE = 1
ELSE
    IF CC(3) +CC(4)+CC(5) >0.6, CC(5) >0.25, CC(3) +CC(4) >0.25 THEN
        SIZE = 6
    ELSE IF CC(5) >0.4 OR RCC(5) >0.5 THEN
        SIZE = 5
    ELSE IF CC(4) >0.4 OR RCC(4) >0.5 THEN
        SIZE = 4
    ELSE IF CC(3) >0.4 OR RCC(3) >0.5 THEN
        SIZE = 3
    ELSE IF CC(2) >0.4 OR RCC(2) >0.5 THEN
        SIZE = 2
    ELSE IF CC(2) +CC(3) > CC(4) +CC(5) THEN
        IF CC(2) > CC(3) THEN
            SIZE = 2
        ELSE
            SIZE = 3
        ENDIF
    ELSE
        IF CC(4) > CC(5) THEN
            SIZE = 4
        ELSE
            SIZE = 5
        ENDIF
    ENDIF
ENDIF

where    CC is canopy closure,
         RCC is relative canopy closure.
```

100,000 acre assessment area was harvested in the first decade. This scenario was modeled to evaluate the consequences of continuing the management emphasis on the 99 acre timber harvest plan throughout the assessment area. The second management situation consisted of modeling harvest on only the 99 acre timber harvest plan area.

In both management situations, no harvest was assumed on National Forest land. Riparian areas were mapped as specified by the State's forest practice rules. Limited selection harvest (postharvest stand must meet CWHR class 4M criteria) was the only treatment allowed in riparian areas. Northern spotted owl activity centers were mapped from recorded sightings. A 1.3 mile circle was drawn around the nest location. The inner 1,000 foot radius circle was designated nesting and roosting habitat with no harvest permitted. The remaining area within the circle was designated foraging habitat. Limited selection harvest was permitted in foraging habitat. In unrestricted areas, even-aged harvest resulted in a CWHR class 2M 10 years after harvest. Selection harvest resulted in a CWHR class 4M 10 years after harvest.

Connectivity

Cumulative impacts were quantified in terms of the connectivity of late successional forest. Late successional stands were defined as those meeting the structure criteria of either 5M, 5D, or 6, using the CWHR classification system. Connectivity was used as a measure of the landscape's suitability as habitat for the Pacific Fisher. For connectivity analysis, the vegetation coverage was relabeled into three categories:

- Core is late successional forest, consisting of CWHR size and density classes 5M, 5D, and 6.
- Matrix is intervening but benign habitat, consisting of CWHR size and density classes 5P, 5S, 4D, and 4M.
- Barrier is intervening and impassable environment. All CWHR categories that are not matrix or core constitute barrier.

The following iterative algorithm estimated the degree of connectivity of late successional forest on the assessment area: core polygons sharing any amount of common boundary were aggregated into a single linked polygon group. Core polygons were also aggregated into a single linked polygon group if they were less than a maximum allowable distance apart and separated by matrix land. Core polygons separated by any amount of barrier land or by matrix land extending farther than the maximum allowable distance were classified as unconnected. This procedure was repeated until no more aggregations of polygons or polygon groups could occur. Classifying the entire assessment area in this fashion resulted in a map of connected polygon groups.

The maximum allowable distance of matrix land between two connected core polygons (analysis scale) estimated the maximum distance that individuals of a particular species can travel between habitat areas. A scale of 3,281 feet (1,000 meters) was used for the analysis of connectivity of Pacific Fisher habitat in this study.

Results

At a scale of 3,281 ft, harvesting the 99 acre timber harvest plan area had a negligible effect on connectivity of late successional forest on the 100,000 acre assessment area. This study therefore concluded that habitat quality for the Pacific Fisher would not be significantly reduced on the assessment area as a result of the proposed harvest. Sensitivity analysis did reveal, however, that connectivity as defined in this study was highly scale dependent.

Harvesting the entire assessment area caused large scale fragmentation of late successional forest and a significant reduction in quality of Pacific Fisher habitat. Without further harvest after the first decade, recovery to late successional forest conditions occurred within the 50 year planning interval on a large part of the assessment area.

Assumptions about harvesting behavior on different ownership categories within the assessment area have the potential to influence the results of connectivity analysis. In this study the Six Rivers National Forest constituted nearly 40 percent of the assessment area in one large contiguous block. If timber harvest had been modeled on National Forest land in this study, the results of the connectivity analysis might have been different.

Restricting harvest in riparian areas and northern spotted owl activity centers had only a marginal mitigation value for the connectivity of late seral forest. These areas were too small to make a meaningful difference in the results at the scale of this analysis.

The translation of tree list data from inventory plots and FVS projections to estimated CWHR classes is sensitive to algorithmic changes. Improvements to future studies should include sensitivity analysis of tree list to CWHR translator algorithms, addressing changes in ownership and management directions, continued harvest throughout the planning interval, adjacency constraints on clearcuts, and effects of catastrophic events such as fire.

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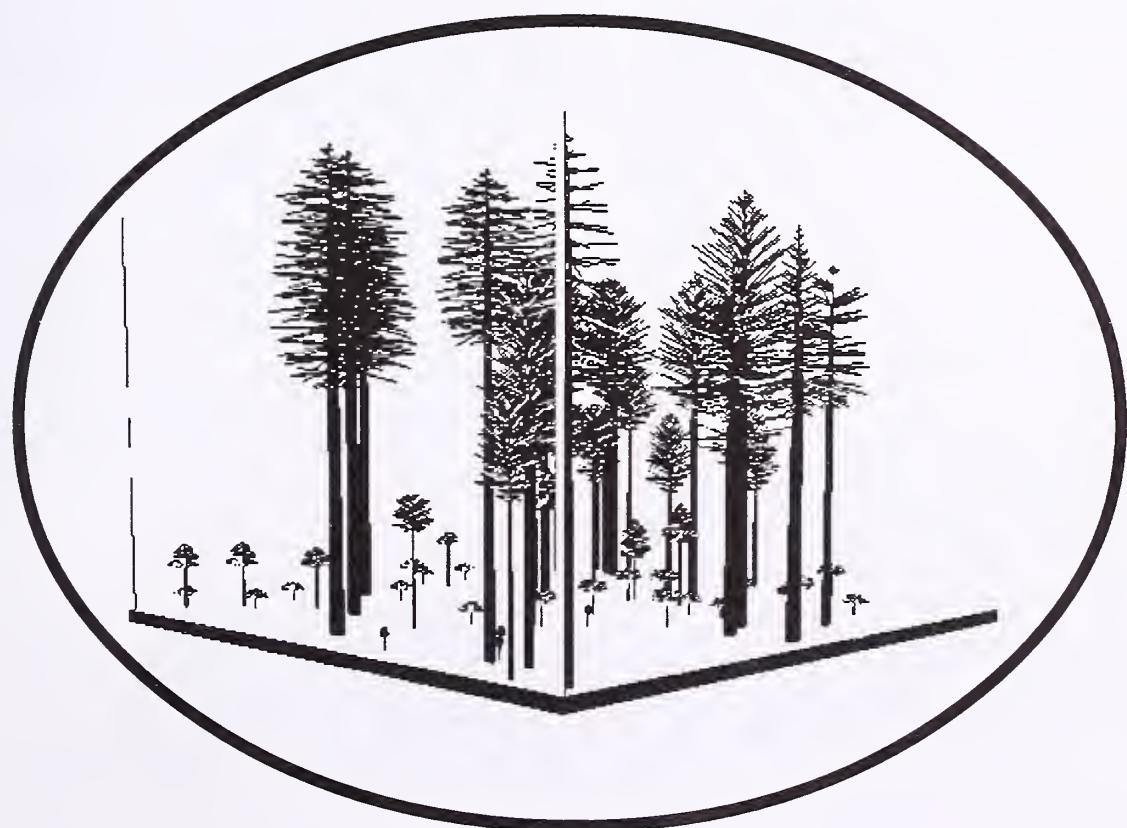
Use of FVS in the Black Hills National Forest Plan Revision

John B. Rupe
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Abstract—In the recently completed Black Hills National Forest Land and Resource Management Plan Revision, the Forest Vegetation Simulator (FVS) was used to analyze the economics and feasibility of alternative timber harvest methods and timing choices. FVS provided data to the Spectrum linear programming model and generated data for the GIS analysis. Ponderosa pine (*Pinus ponderosa*) dominates the Black Hills National Forest in South Dakota and Wyoming. Typically, ponderosa pine stands are not uniform in size, age, or density. This can cause special problems in the Spectrum model, which does not handle multi-aged or mixed strata well. However, FVS was able to simulate the full range of conditions on the Forest under a variety of management scenarios alleviating some of the limitations of the Spectrum model. The flexibility, speed, and convenience of FVS should result in a wide array of applications for other planning efforts.

History

The Black Hills National Forest has a unique management history. Sawmills were established as early as the 1870's and the first timber sale in any National Forest was here in 1897. Most every acre on the Forest has been cut over at least once. The first Forest Plan for the Black Hills National Forest was approved in 1983. The Forest Plan revision process began in 1989. One of the most important aspects of the Forest Plan that needed to be revised was the Allowable Sale Quantity (ASQ). Many people believed that the ASQ was calculated too high in the original Forest Plan (although to be fair, others believed it was just right, or even too low).

The 1983 Forest Plan used RMYLD (Edminster 1978) for modeling the ASQ. This growth and yield model uses average stand conditions for input that does not adequately reflect the multi-aged, mixed strata present in the Black Hills. It was decided back in 1989 that with the need to revise the Forest Plan, the use of an individual tree model was appropriate. The GENGYM (Edminster and others 1990) model was integrated into the Stand Prognosis Model (Wykoff and others 1982) in order to accomplish this need.

When plan revision first started, PROGNOSIS would only run on the Department of Agriculture's UNIVAC mainframe in Fort Collins. However, this platform was determined to be too expensive and impractical. Within 3 months of the first meeting between representatives from the Forest Service Rocky Mountain Regional Office and the Forest Management Service Center at Fort Collins, a Data General (DG) version of PROGNOSIS was available.

While work progressed on the Draft Forest Plan, changes were being made to the GENGYM version of the PROGNOSIS model. At some point it was determined that the PROGNOSIS runs were severely impacting the Forest's Data General computer and, therefore, a decision was made that the simulations would only be done at night and on weekends. When it was determined that additional simulations were needed between the Draft and Final Forest Plan, an alternative to processing the simulations on the Data General was necessary.

Somewhere around 1993/1994, Prognosis was renamed FVS, which stands for the Forest Vegetation Simulator (Teck and others 1997) and the software was migrated to the DOS operating system. FVS simulations for the Final Forest Plan were made on a Pentium PC using batch files that would run continuously overnight 14 hours at a time.

FVS Support

Without the full and immediate support from the Washington Office Detached Timber Management Staff located at the Forest Management Service Center (FMSC) in Fort Collins, the Forest Plan would not have been completed. From the very beginning, the FMSC personnel were there to help and guide the Forest planning team in the use of the FVS model.

Thousands of simulations were processed, a number of problems were discovered, not only by the planning team, but by the FMSC. The problems ranged from small ones, such as seedlings growing 6 feet in 1 year to larger problems such as the mortality algorithm acting as a thinning, thus preventing stand stagnation from setting in. Each problem was solved quickly and accurately by FMSC personnel.

Prior to executing the FVS simulations, the Forest Planner, the Forest Silviculturist, and members of the FMSC needed to determine what output from FVS was required for the Spectrum input files. This would not only include what data was needed but also in what format. In the case of the Black Hills Plan Revision, the planning team decided that a comma delimited file was needed for exporting FVS data into an intermediate file in Paradox prior to importing the data into Spectrum.

ASQ Committee

One person running FVS will probably not catch all of the problems that can develop. The Black Hills National Forest formed an ASQ committee comprised mainly of District Silviculturists who met frequently to review the FVS simulation results and make suggestions on volumes, prescriptions, needed constraints, errors, and other problems. Occasionally, members of the committee would be asked to help with the simulations while they were being formulated.

Strata Delineation

Before the Planning Team makes any growth projections, we recommend that you form a committee to help formulate the Forest strata. It is very important that the strata delineations be carefully thought. One of the most important decisions made at the beginning of the Black Hills Plan revision was that the stratum must be identifiable on the ground and in the Rocky Mountain Resource Information System (RMRIS) data base. The purpose of that decision was so that the planning team would be able to verify the solutions produced by the Spectrum model using geographic information system (GIS) analysis procedures. Stratum delineation and recognition from the corporate data base was also essential if the Forest was going to be successful in monitoring the Forest Plan.

The stratum on the Black Hills were comprised of four attributes: Forest type, size class, density class, and site productivity class. An example would be the PP9MH stratum that represents ponderosa pine, sawtimber size class, medium density, and high site index. There were 17 stratum in the Black Hills Forest Plan.

Silvicultural Matrix

Constructing a matrix of silvicultural prescriptions to run through the FVS model is very beneficial and may as well be considered essential. Each prescription represents a unique combination of treatments and timing choices. Having your planning team buy-off on the full matrix, which is comprised of your strata on the x-axis, and your silvicultural prescriptions on the y-axis, will greatly reduce the amount of time you spend on developing your yield tables for Spectrum. The more preparation work you can do on the front side of the analysis the better, as it will allow you to design a very efficient set of batch files for processing your simulation results.

The matrix should be large enough and positioned so the person responsible for running FVS can see the individual prescriptions by stratum. Once a cell (a unique combination of stratum and prescription) in the matrix has had its FVS keyword file(s) created, the simulations have been run, and the committee has evaluated the results, then the cell on the matrix can be crossed out as completed. As simulations are evaluated, the person running the model needs to be able to indicate on the matrix that a cell is finished, or modifications

are needed, or that the cell has been eliminated for consideration in the Spectrum solution.

The initial silvicultural matrix on the Black Hills consisted of no management simulations as well as those prescriptions used in the 1983 Forest Plan. A numbering system was used to represent the silvicultural prescriptions. We recommend Forest planning teams consider using this technique as it works quite well and is very responsive to unforeseen changes in your matrix. Inevitably, no matter how well the planning team designs the matrix, there will always be a few additional prescriptions someone will ask you to evaluate in response to some issue that gets raised during the revision process.

We recommend that a committee be formed to evaluate the simulation results. This is done to determine the feasibility of each prescription. Many of the prescriptions that we first thought would be part of the Spectrum yield tables were modified or eliminated due to this evaluation process. The decision rules to determine prescription feasibility will vary from Forest to Forest. Our analysis included evaluating what percent of a stratum received a prescribed treatment as a function of local developed merchantability requirements. This sort of analysis is done in order to provide the Spectrum model with a reasonable number of alternative prescriptions that cover the full range of alternatives.

There were only a few constraints used in FVS that would cause a harvest not to take place. One was the minimum harvest constraint (MINHARV keyword). On the Black Hills, 1,000 board feet per acre was used. Another constraint was 25 overstory sized trees per acre must be present before the seed-step of a shelterwood prescription could be performed. Finally, 300 trees per acre (mostly seedlings) must already be established prior to allowing the overstory removal of a shelterwood.

Batch Processing Files

At the time the Forest Plan was being developed, FVS was not yet available on the corporate IBM RISC-6000 workstations. Therefore, FVS still processed fastest on a PC platform (with full 615 implementation, FVS will be available for both windows operating systems on a PC as well as the UNIX operating system on work stations). The FVS simulations for the Draft Forest Plan were done on the Data General computer. The FVS simulations for the Final Forest Plan were done on a PC with a 120Mhz Pentium Processor. FVS seemed to process more than 10 times faster on the PC compared to the Data General.

Batch file processing worked extremely well on the PC Pentium. Once the batch files were set up, the base set of keyword files could be changed to run other prescriptions and/or stratum. With Richard Teck's help from the FMSC, the Forest was able to set up runs that ran up to 14 hours at night on the PC. This included commands for transferring simulation results to various directories for subsequent post-processing into Spectrum formatted reports, compressing simulation results for archival purposes, deleting intermediate results, and renaming files.

Using The Stand Visualization System _____

The Stand Visualization System (SVS) (McGaughey 1997) was used throughout the FVS modeling process, mainly to troubleshoot and proof the simulation results for any problems that might exist. You know the old saying that a picture speaks a thousand words. Many times SVS was used to discover problems such as harvests not taking place when scheduled, particular species such as aspen and white spruce growing larger than expected, and so forth.

When a SVS movie is created it can visually illustrate to our internal groups as well as to our publics what is planned. It really helps when the Forest can show what a seed-cut of a shelterwood will look like compared to a seed tree cut or an overstory removal.

Other Resource Attributes _____

FVS is a very powerful model in that it can be used to calculate user-defined indices based on a combination of edaphic features and vegetative conditions. We used FVS to calculate the following indices, some of which were used by Spectrum as yield tables, some as constraints, and some were incorporated directly into spatial analysis of the Spectrum solution using GIS.

Timber Volumes—The following volumes were needed for Spectrum: (1) merchantable sawtimber board feet; (2) merchantable sawtimber cubic feet; (3) products other than logs (POL) cubic feet; (4) harvested merchantable sawtimber board feet; (5) harvested merchantable sawtimber cubic feet; and (6) harvested POL cubic feet. Calculating all of these volumes required three separate runs per prescription and was extremely difficult to keep track of, especially making sure the batch runs were set up correctly. The third run was necessary strictly for top wood volume in cubic feet for each of the above.

Fire Hazard—FVS calculated the fire hazard of High, Medium, and Low, using three slope classes and Vegetative Structural Stage (VSS) calculations. Much better equations are available today.

Beetle Risk—The mountain pine beetle (*Dendroctonus ponderosae*) is the most damaging agent in the Black Hills. The beetle risk algorithm used in FVS was based on a local study conducted by John Schmitt, recently retired entomologist, which uses size class, basal area, and quadratic mean diameters as parameters.

Snag Density—Snag density was based on mortality, three size classes, and includes a snag fall rate from a local Forest study.

Forage—Pounds of forage per acre was calculated for two soils, crystalline and noncrystalline.

Habitat Structural Stages—Wildlife biologists determined the parameters needed locally for the habitat structural stages. This rule base was incorporated into the Black Hills keyword file and uses size class, age, and stand density index (SDI) as the parameters.

Stand Age—Ages of the stands were tracked through the planning period.

Thermal Cover—Average maximum densities and top height were used to calculate thermal cover.

Regeneration Entry—Regression equations were used to establish natural regeneration. The equations were based on relative density, number and size of overstory seed-producing trees, and existing regeneration.

Percent of Plots Cut (POPC)—Because there were constraints in the FVS model that would determine whether a stand received a scheduled treatment, the percent of stands receiving a particular harvest was calculated. Spectrum then used these figures to determine the cost of treatments and the feasibility of alternative harvests.

Interfacing With Other Models _____

FVS was only one of a suite of tools used in the Revision effort. The major models used included FVS, Spectrum, ARC/INFO, and GIS-HABCAP. In particular, FVS and Spectrum work very well together. FVS was used as a simulation tool for each strata, to evaluate alternative prescriptions, and to generate board feet yield tables, cubic feet yield tables, in addition to the "other resource" yield tables described above. Spectrum was used as a linear optimization tool for the Forest as a whole, and it was used to select among the silvicultural alternatives simulated with FVS.

It was easy to move data from FVS into Spectrum. A routine was written in FVS to output the results for a strata into an ASCII/TEXT file delimited by commas. Since data for Spectrum is stored in dBASE format files, a PC data base program (PARADOX) was used to import the comma delimited data into the dBASE files.

Within Spectrum, the timber harvest level over time was calculated. In addition, other environmental effects for the Forest over time were estimated using data from FVS: fire hazard, mountain pine beetle hazard, wildlife habitat structural stages, big game thermal cover, forage production, and number of snags (dead standing trees).

After the Spectrum model was run, the following additional environmental effects were estimated and evaluated using ARC/INFO: suitable wildlife habitat, water yield, economics, and scenic integrity.

Modeling Stand Variability _____

As discussed earlier, a crucial issue in the Revision was that some individuals and groups believed that the previous timber harvest level set in the original Plan was too high. One of the possible causes of an overestimate could have been the use of a whole stand simulator, where each strata was entirely assumed to be the same age and size. Within each strata, there is tremendous variability in age, size, amount of regeneration, and in timing of the appropriate harvest.

To better account for the variability within each strata, a different approach was used in the Revision effort. Typically, FVS simulations are run with a single timing sequence

of harvests, and that simulation is transferred to a model like Spectrum as one timing choice. Then Spectrum is used to select among all of the individual timing choices. In the modified approach, an FVS simulation was used to represent a composite of different timing choices. This composite is a result of all of the different timing choices developed for the plots which comprise the strata.

The composite was represented by displaying the percentage of the strata ready to be harvested in each decade of the simulation. This percentage was based on the percentage of plots cut (POPC). A POPC was developed for each harvest in the simulation based on the percentage of plots in the strata that met minimal requirements for that harvest. These minimal requirements included the presence of regeneration, minimal basal area requirements, and minimal volumes per acre.

For instance, one prescription might be to thin in the next decade (decade 1), then do a seedcut no earlier than 20 years later (decade 3) if there is sufficient volume. Finally, no earlier than 20 years after the seed cut (decade 5) do an overstory removal if there is sufficient regeneration. In this example, there are 20 plots in the strata. In decade 1, if there was sufficient volume to do a thin in 15 plots, the POPC for the thin in decade 1 is 0.75. Likewise, a POPC is developed for other harvests in the scenario.

For final harvests, a second final harvest is included in the simulation so that entire strata will be covered. For instance, if the POPC in decade 5 for the overstory removal is 0.80, another overstory removal is modeled in decade 6 for the remaining plots (0.20).

Within the SPECTRUM model, the POPC coefficient is used to represent the effective acres of harvest when the prescription is selected in the simulation. For instance, if 10,000 acres were selected, and the POPC for thinning in the first decade for the prescription was 0.80, then the actual acres of thinning is 8,000 acres.

Conclusions

Together with the SPECTRUM model and other tools, the FVS model was critical for the development of the Black Hills Revised Forest Plan. FVS and Spectrum work very well together, and it is easy to move data back and forth between the models.

For the final simulations used in the Plan, FVS was run using batch files on a PC. Some of these batch runs ran up to 14 hours overnight. As a visual aid, a matrix of all of the simulations that were needed was developed. The Stand Visualization System was also valuable for evaluating simulation results.

For a Forest with high variability within each strata, composites of prescriptions can be developed by estimating the percentages of plots cut for each harvest in the simulation. These percentages can be moved into the SPECTRUM model in calculating the exact acres of harvest when prescriptions are not applied uniformly within the strata.

The Black Hills National Forest Plan Revision took many years to complete. Nonetheless, it is one of the first completed Forest Plan Revisions in the Forest Service. FVS was instrumental in completing the Forest Plan Revision. Over the course of time, there have been many, many improvements and enhancements to the FVS software. Other Forests going through Forest Plan Revision should benefit greatly from the Black Hills experience—lessons learned, things to do, things not to do, and recommended procedures. For more information, contact the authors or the Forest Management Service Center in Fort Collins (970-498-1772).

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Using FVS to Prepare the Custer State Park Resource Management Plan

William Hill

Abstract—Custer State Park is a large multiple use park where the dominant vegetation is ponderosa pine. Past management practices and recent wildfires have created a variety of stand structures. The Resource Management Plan was designed and written in holistic fashion; public input was collected from a focus group before the plan was written. To prepare the plan, Spatial Analysis Systems (SPANS®) GIS and the Forest Vegetation Simulator (FVS) were used. FVS was used to individually model each stand. Uninventoried stands were also modeled using phototype expansion through RMSTAND. Each individual keyword file was created using templates for managed and unmanaged stands. Output from the model, needed for spatial representation in the plan, had to provide current forest attributes, predicted harvest levels, and predicted future attributes. Files or databases were built to be imported and linked to the GIS. Maps were built with the GIS so that the entire forest condition could be analyzed and appropriate planning measures taken.

Custer State Park is a 70,000 acre multiple use State park located in the Black Hills of South Dakota. The park has approximately 50,000 acres of forest land and 20,000 acres of grassland. The commercial species in Custer State Park are ponderosa pine (*Pinus ponderosa*) and white spruce (*Picea glauca*). Over 99 percent of the area in conifer forest is composed of ponderosa pine. Various deciduous hardwood species are also present, most notably paper birch (*Betula papyrifera*), quaking aspen (*Populus tremuloides*), and bur oak (*Quercus macrocarpa*). In 1988 and 1990, two major wildfires destroyed approximately 13,000 acres of timber while leaving slightly more than 6,000 acres of forest land in varying states of survival.

One of the main reasons these fires occurred at such high intensity was the past history of forest management in the park and the resulting forest condition. Between 1919 and 1980, timber harvesting was sporadic. Almost no timber stand improvement (TSI) work, an aggressive fire suppression program, and light sanitizing cuts of overmature pine led to stand conditions of very dense, small pine with an overstory of old, decadent pine. In 1980 a forest plan was written, outlining directions to regulate the stagnated forest condition through harvesting of overmature trees and non-commercial thinning of the dense immature stands. An

annual harvest level of about 3.5 million board feet (MMBFT) was set. The regulation activity proceeded until the major fires occurred. After the smoke cleared it was very obvious a new plan was needed to carry out the management of this partially burned, partially managed landscape.

The Resource Management Plan of 1995 was written in a holistic fashion (Walker and others 1995). Holistic resource management is a way of managing resources in any terrestrial ecosystem to produce a desired goal. Spelling out a three part goal that includes quality of life, production, and landscapes are of paramount importance (Center for Holistic Resource Management 1989). The Resource Management Plan of 1995 incorporated owner (citizens of the State of South Dakota) involvement from the very start to formulate these goals. Public participation for the plan was done initially by using a focus group composed of representatives of the users of Custer State Park. The focus group assisted in forming goals and formed a consensus for the future direction of the park. This is important to note because, except for preliminary tests and experimentation, there was no modeling done before public participation began. By the time public participation was completed and before the plan was finalized, the focus group and the general public affirmed our desire to continue with the process of managing the stands not entered during the regulation period. It was agreed to keep the harvest level at approximately 3.5 MMBF as in the previous plan, and if needed, follow with non-commercial thinning. It was also agreed to enter the stands managed during the regulation period as soon as possible, and not enter any of the stands surviving the major wildfires until after the unmanaged stands were entered. A finite planning scope of 15 years was decided on; all planned events and predicted results would not exceed the year 2010.

Early in the planning process the park decided that GIS technology would be used in preparing the plan. Because of its superior analytical functions, Spatial Analysis System (SPANS®) from Intera Tydac was selected. At the time, this software was operating system specific: OS/2 on a PC and AIX (UNIX) on the IBM RS/6000 work station. We chose to concentrate most GIS activity on the work station, because at the time PC technology would not effectively handle the analysis we needed to do. Creating polygons from our large vector file would take almost an entire work day on the PC, whereas the work station would accomplish the task in a few minutes.

Simultaneous to the public participation process and decisions on GIS, we were conducting the first large scale, stand level inventory in Custer State Park. We needed data to write a plan, so we furiously conducted an inventory on a shoestring budget. We also needed software to process the inventory data and a growth and yield model to predict what

was going to happen to the forest in the future. Because we were spending all of our money on the GIS, there was little money to spend on other software. After considering a commercial software package, Stand Projection System (SPS), (Arney 1985) and two other public domain programs, RMYLD (Edminster 1978), and GENGYM (Edminster 1991) we decided to use FVS (Central Rockies Variant) that was well integrated with RMSTAND. RMSTAND is the inventory and stand exam program for U.S. Department of Agriculture, Forest Service, Rocky Mountain Region. The price was right for this apparently powerful public domain software but it was not yet available for AIX. The source code was however, and because we had the proper compilers we assumed it would simply be a matter of compiling the code on our work station. Without knowledge of the complexity of the source code and FORTRAN programming this turned out to be impossible. To make a long story short, to this day I have been getting very functional "black market" copies of FVS, compiled for the RS6000 from sympathetic Forest Service employees and I have paid to have a programmer compile RMSTAND as well as FVS post-processors. It should be noted that as of this writing FVS, the Submittal System and the post-processors are now available for the AIX operating system.

Using FVS to Prepare the Plan ____

Custer State Park has approximately 350 individual forest stands identified. When the time had come to model growth and yield of the forest we had 55 percent of the stands inventoried. Because the GIS was going to need attribute data for every polygon, I decided that all stands should be modeled. But how was I going to do that without inventory data for each stand? I devised a method loosely based on what Jim Arney called phototype expansion (Arney 1992). Arney described a process where stand polygons that have not been field sampled and have distinct vegetative stratification (phototypes), are assigned stand average estimates of species, size, and volume expansions from sampled stands of the same strata. My method worked by grouping all inventoried stands of a particular phototype using the JOIN utility in RMSTAND. The data from the joined stands was then processed in RMSTAND using the Combined stand run option. Effectively, all the plots taken in a phototype were run through the inventory software as one stand, producing attributes and an FVS tree data input file for the phototype. The attributes of the phototype were then assigned to all of the uninventoried stands of that phototype. For example: One of the most common phototypes in the park was what we call P4P1—unmanaged (large pine sawtimber over pine seedling/sapling understory). These stands that were sampled during the inventory were joined together, processed through RMSTAND creating one FVS tree file. The FVS file was then copied to tree files for these stands. This was repeated so all stands, sampled and unsampled, had a tree file.

I then needed to create keyword files for all the stands. Because the Submittal System was not available for the UNIX operating system at the time this analysis was performed, this task was done manually for each individual stand. I did use some shortcuts though. I first wrote a series

of templates, one for unmanaged stands, one for managed stands, and one for the fire damaged surviving stands. Unmanaged stand templates had a series of keywords that had the event monitor look at the stand condition and perform a cut based on the condition it encountered. I also forced cuts in unmanaged stands so that approximately 3.5 MMBF per year would be harvested. This was done grouping management units together, based on inventory data, and using the TIMEINT keyword to schedule harvests by year to approximate this volume. Managed stand templates had a series of simple keywords that triggered a cut when a minimum volume could be removed while leaving an acceptable residual basal area. Fire surviving stands were projected without management. The templates all had these keywords in common: DESIGN, STDINFO, SITECODE, STDIDENT, BFDEFECT, MCDEFECT, VOLUME, GROWTH, INVYEAR, NUMCYCLE, SDIMAX, TIMEINT, MINHARV, TREELIST, ECHOSUM, SPECPREF, CHEAPO, END, PROCESS, and STOP. See appendix A for an example keyword file built from the template. This example of an unmanaged stand keyword file contains all of the keywords mentioned above, necessary for processing each stand.

I did have to manually edit these keywords in each individual keyword file: STDINFO (age), SITECODE (site index), STDIDENT, INVYEAR, TIMEINT and MINHARV. At this point I had keyword files and tree data files to make runs, but I was faced with two problems: (1) I needed a way to edit the keyword files, but not one at a time and (2) I needed output that would link to the GIS in a relatively easy fashion.

The first problem was solved by using two utilities common to all versions of UNIX, sed and awk. Sed is an acronym for stream editor and awk stands for Aho, Weinberger, and Kernighan, the authors of awk (Dougherty 1992). These utilities are actually UNIX programs that have the ability to edit multiple text files at once. I used sed almost exclusively to make changes in the keyword files such as changing TIMEINT, stocking levels in thinning keywords, and adding keywords to create output that would interface with the GIS. Obviously, this was a very powerful tool that allowed me to forgo making these types of changes to each individual file. See appendix A for an example of a sed input file containing changes made to all of the keyword files during one run, using sed. This is also a good lead-in to discuss the answer to the second question regarding output linked to the GIS.

To spatially display present and future stand conditions, and analyze those conditions with the GIS, I needed FVS output that went beyond the information provided in the standard output files and was compatible with the GIS. I needed information such as average d.b.h., basal area, trees per acre, board foot harvested (but at custom diameter ranges), and I needed some custom information such as vegetative structural stage, and size class. It was at about this time that I "discovered" the COMPUTE post-processor. Richard Teck customized a version of this program for me so that it "looked" for the STANDID in a specific field where I had been placing it, and then placed it in the output file in the first field, instead of year. Note the COMPUTE keywords in appendix A that are a part of a sed input file and were used to generate custom variables for vegetative structural stage and size class.

Linking FVS to SPANS® GIS _____

In the process used to link FVS runs to the GIS, the first step was to run sed on my keyword templates subtracting and adding keywords as needed. The next step was to run the stands in batch by management unit (compartment).

This UNIX script file shown in figure 1, written by Nick Crookston, allows running FVS from the command line without entering the names of input and output files. By simply writing a text file that repeated the command line syntax for every stand in the batch file that I was running, multiple stand runs were possible. Stand simulations were grouped by compartment for organization, and because the COMPUTE post-processor looks for output files with a common runstream name.

The COMPUTE post-processor was then run on each compartment extracting the specific variables that were needed for the GIS. A sed file was then run on each compute output file (management unit) stripping the header and importing the variables for a particular year and then concatenating them to a new output file (fig. 2). A SPANS header was added to this ASCII file telling the GIS the format of the data, and it was then imported into SPANS.

At this point the FVS generated data is in a table or database within SPANS. A process within SPANS called table modeling was then used to link the data to an existing database within SPANS containing the vital information of geographic location and stand ID (fig. 3). The new table/database could then be used to reclassify the base entity map for any variable that was imported.

Retrospective Analysis _____

The approach I used to integrate FVS with SPANS GIS to prepare the Custer State Park Resource Management Plan, was far from seamless. As an average computer user, I was able to construct a way through it though, but there were too many seams and too much time spent there. I believe one of the next logical steps in the evolution of FVS should be output formatted for the major GIS software on the market.

Two of the biggest problems that I encountered while using FVS during this period were no official support for a UNIX version and not being a Forest Service employee (in the loop). The "black market" AIX versions of FVS performed flawlessly (to my knowledge) but I had to ask the parties involved if they had or could compile a new release for me. This ties to the second problem. Without a connection to the Forest Service, except a telephone, I never knew when there were changes to FVS and whether I might need a new version. All this is rapidly changing with the proliferation of the internet and the 615 project. I am now notified by e-mail

```
FN = `echo $2 | cut – d. – f1`
cat << !!! > $$.temp
$FN.key
$FN.tre
$FN.out
$FN.tls
$FN.sum
$FN.chp
!!!
$1 < $$.temp
rm $$.temp
find $FN.* – size 0 – exec rm {} \;
```

Command line syntax

```
rr cr 2172001  Where rr = the above script file executable,
cr = FVS executable, and  2172001 = stand id #
```

Figure 1—UNIX script file for processing on command line; associated command line syntax.

	Year	VSS	Size
2172001	1982	31.00	3.00
2172001	**1995**	**31.00**	**4.00**
2172001	2005	31.00	4.00
2172001	2010	31.00	4.00
2172001	2020	31.00	4.00
2172001	2030	41.00	4.00
2172001	2040	42.00	4.00
2172002	**1995**	**32.00**	**3.00**
2172002	2005	33.00	4.00
2172002	2010	43.00	4.00
2172002	2020	42.00	4.00
2172002	2030	42.00	4.00
2172002	2040	42.00	4.00
2172002	2050	41.00	4.00
2172002	2060	41.00	5.00
2172003	1982	41.00	4.00
2172003	**1995**	**41.00**	**4.00**

2172001 2030 4.00 – – – – – –>

New file to be imported into SPANS

2175003	1995	31.00	3.00
2171005	1995	41.00	5.00
2171006	1995	42.00	4.00
2172001	**1995**	**31.00**	**4.00**
2172002	**1995**	**32.00**	**3.00**
2172003	**1995**	**41.00**	**4.00**

Figure 2—Stripping data from COMPUTE output file using sed; concatenate to new file.

Header added

```
ID vss2010
TITLE vss2010
TABTYPE 4
FTYPE free
KEYFIELD 1
NRECORD 351
1 3 8.000000 0 Attr0 Attr0
2 4 4.000000 0 Attr1 Attr1
3 1 7.100000 0 Attr2 Attr2
4 1 7.000000 0 Attr3 Attr3
DATA
2001    2010    41.00    5.00
2003    2010    42.00    4.00
2004    2010    42.00    4.00
2005    2010    41.00    4.00
2002    2010    43.00    4.00
8002    2010    41.00    4.00
8008    2010    42.00    4.00
8009    2010    42.00    4.00
10002   2010    43.00    4.00
31002   2010    43.00    4.00
```

Link to existing database

```
ID stage10
TITLE standid, entity & vss
TABTYPE 2
FTYPE free
KEYFIELD 3
NRECORD 351
1 0 8.500000 0 lat lat
2 0 10.500000 0 lon lon
3 3 10.000000 0 standid standid
4 6 6.000000 0 standent standent
5 1 2.000000 0 vss vegetative structural stage
DATA
43.77733   -103.49192   2173006   1560   41
43.77993   -103.49506   2004      1558   42
43.77950   -103.48699   2173002   1568   41
43.78258   -103.48952   2173003   1575   41
43.78388   -103.49315   2045      1607   0
43.78742   -103.49589   2003      1576   42
43.78778   -103.49357   2001      1573   41
43.78605   -103.49266   2002      1574   43
43.78560   -103.49068   173015    2144   0
```

Figure 3—Adding SPANS header to database and appending (using table modeling function) to existing database with geographic information, using the stand ID as the key link.

of changes to the software, all of the FVS software is available in AIX format and can be obtained via the U.S. Forest Service's World Wide Web site in Fort Collins, CO (ftp://162.79.41.7).

The Forest Service support for FVS itself is excellent. Without the help and suggestions from Richard Teck and Gary Dixon, the quality of information in our plan would be significantly lower. Examples of calculating variables within the COMPUTE keyword and how one National Forest was using them in GIS integration was extremely helpful.

The strengths of FVS for someone in my position is its robustness and the portability of its output. Given the time, FVS could be used to model countless forest management scenarios. The flat ASCII input and output files used by FVS are easily manipulated by text editors. This allowed a computer user of my skill level to edit input quickly with batch editors and link the output relatively simply. At one point in time, we considered commercial software that would have to be customized for our area but frankly we did not have the money or stomach for the risk. The price of FVS was right, it is a powerful model that was available immediately, and it used growth equations developed from Black Hills research. Using FVS, we were able to write a state of the art plan in an affordable fashion and a short period of time.

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Appendix A

<div align="center">

Example of keyword file for unmanaged stand

</div>

```
DESIGN            1         1         999       1         1
STDINFO           203       3         83                            55
SITECODE          10        70
STDIDENT
 2401015                    BACHELOR DRAW #1   STAND 15
COMMENT
STAND WAS NOT LOGGED DURING FIRST ENTRY DURING REGULATION PERIOD.
MOST OF IT IS INOP AND CAN NOT BE LOGGED CONVENTIONAL
SCHEDULE INITIAL HARVEST AFTER 2001.
MAINTAIN STAND AT 60 BA IN FURTHER ENTRIES AT MINIMUM HARVEST OF 2000 BF
END
MGMTID
THIN
BFDEFECT                              .30       .20       .25       .25       .30
MCDEFECT                              .25       .15       .20       .20       .25
VOLUME                                8         7.0
GROWTH            0         10        0         5         5
INVYEAR           1992
NUMCYCLE          8
IF                99
YEAR GT 2001 AND SPMCDBH(1,10,0,0,6) GT 600 AND SPMCDBH(4,10,0,8) GT 2000 &
AND AGE GT 120
THEN
THINDBH           0         12        999       1.00      10        0
THINDBH           0         0         8         .30       10
IF                99
YEAR GT 2001 AND SPMCDBH(1,10,0,0,6) LT 600 AND SPMCDBH(4,10,0,8) GT 4000
THEN
THINBBA           0         60                  6         999
THINDBH           0         0         6         .30       10
IF                99
YEAR GT 2001 AND SPMCDBH(1,10,0,0,6) GT 600 AND SPMCDBH(4,10,0,8) GT 4000 &
AND AGE LT 120
THEN
THINBBA           0         60                  6         999
THINDBH           0         6         999                 10        60
IF                99
YEAR GT 2001 AND SPMCDBH(2,10,0,0) LT 100 AND SPMCDBH(1,10,0,0,6) LT &
300 AND SPMCDBH(4,10,0,8) GT 4000 AND AGE GT 165
THEN
THINDBH           0         8                             10        30
IF
CUT EQ YES AND (AADBH LT 8.0 AND NOT AADBH GT 3.0) AND ATPA GT 450 &
AND AGE GT 100
THEN
THINBTA           2         300                 0         6         2
IF
CUT EQ YES AND (AADBH LT 8.0 AND AADBH GT 3.0) AND ATPA GT 450 AND &
AGE GT 100
THEN
THINBTA           2         200                 0         6         2
IF
CYCLE GT 4
THEN
THINDBH           0         0         6         .30       10
THINBBA           0         60                  6         999
ENDIF
MINHARV           5                   2000
SDIMAX                      408       0         6
TIMEINT           1         3
TIMEINT           2         6
TIMEINT           3         2
VOLUME                                8         7.0
TREELIST          1         3         1         0
ECHOSUM
DELOTAB           1
DELOTAB           2
SPECPREF          1         5         -9999
SPECPREF          1         8         -99
CHEAPO            13
```

Example of sed input file to delete keywords and then add COMPUTE keywords to calculate custom variables

```
# Deletes existing COMPUTE keywords and adds keywords to calculate\
# vegetative structural stage and size class
/\*/,$d
/CHEAPO/a\
*\
*calculates vegetative structural stage (VSS) for pine stands\
*\
COMPUTE             0\
MAXSDI=408\
SDI2=SPMCDBH(1,10,0,0.00,0.99)*(SPMCDBH(5,10,0,0.00,0.99)/10)**1.65992\
SDI3=SPMCDBH(1,10,0,1.00,8.99)*(SPMCDBH(5,10,0,1.00,8.99)/10)**1.65992\
SDI4=SPMCDBH(1,10,0,9.00,99.99)*(SPMCDBH(5,10,0,9.00,99.99)/10)**1.65992\
SDI=SPMCDBH(1,10,0,1.00)*(SPMCDBH(5,10,0,1.00)/10)**1.65992\
%SDI=(SDI/MAXSDI)*100\
BA2=SPMCDBH(2,10,0,0.00,0.99)\
BA3=SPMCDBH(2,10,0,1.00,8.99)\
BA4=SPMCDBH(2,10,0,9.00,99.99)\
VSS1=MAXINDEX(BA2,BA3,BA4)+1\
VSS2=LININT(%SDI,39.99,40,59.99,60,1,2,2,3)\
END\
IF                  0\
%SDI LT 10 AND SPMCDBH(1,10,0,0.0,0.99) LT 200\
THEN\
COMPUTE             0\
VSS1=1\
END\
ENDIF\
IF                  0\
%SDI LT 10 AND SPMCDBH(1,10,0,0.0,0.99) GT 200\
THEN\
COMPUTE             0\
VSS1=2\
END\
ENDIF\
IF                  0\
CYCLE GE 0\
THEN\
COMPUTE             0\
VSS=(VSS1*10)+VSS2\
END\
ENDIF\
IF                  0\
VSS1 EQ 1\
THEN\
COMPUTE             0\
VSS=1\
END\
ENDIF\
IF                  0\
VSS1 EQ 2\
THEN\
COMPUTE             0\
VSS=2\
END\
ENDIF\
*\
```

```
* Calculate size classes\
*\
COMPUTE              0\
BASAP=SPMCDBH(2,10,0,1.00,4.99)\
BAPOLE=SPMCDBH(2,10,0,5.00,8.99)\
BASAW=SPMCDBH(2,10,0,9.00)\
BALARGE=SPMCDBH(2,10,0,9.00,15.99)\
BAVLARGE=SPMCDBH(2,10,0,16.00)\
SIZE1=MAXINDEX(BA2,BASAP,BAPOLE,BASAW)\
END\
IF                   0\
SIZE1 EQ 4\
THEN\
COMPUTE              0\
SIZEBIG=MAXINDEX(BALARGE,BAVLARGE)+3\
END\
ENDIF\
IF                   0\
SIZE1 GE 4\
THEN\
COMPUTE              0\
SIZE=SIZEBIG\
END\
IF                   0\
SIZE1 LE 3\
THEN\
COMPUTE              0\
SIZE=SIZE1\
END\
ENDIF\
IF                   0\
VSS EQ 2\
THEN\
COMPUTE              0\
SIZE=1\
END\
ENDIF\
PROCESS\
STOP
```

Integration of the FVS Model with the Ecological Allocation Model

David W. Wilson

Abstract—Menominee Tribal Enterprises has begun major changes in the management of the Menominee Indian Reservation forest in Wisconsin. Based on a concept termed "featured forest cover types," the forest management is guided more on ecological considerations. To implement this new approach to forest management, the foresters turned to the TEAMS/M and FVS models as the decision support tools. TEAMS/M is a hierarchical model that provides alternative paths to reach the legacy forest goals. Volume estimates for the different management alternatives were developed from the FVS— Lake States TWIGS Variant. The integration of the two tools is providing invaluable information for the future management of the forest.

The Menominee Reservation forest in Wisconsin has been intensively managed ever since the reservation was established in 1854. While initial methods of forest management might be considered simplistic in today's terms, they did provide the foundation for what is followed today. The tribal leaders realized that they had to survive off of the 235,000 acre forest and set a plan that cut from the east to the west in such a manner that when finished, the harvest cycle could be repeated infinitum. In 1890, the Federal government was petitioned to allow tribal members to cut green timber. As part of the agreement, Congress required that a set limit of harvest be calculated. Foresters were enlisted and an allowable cut of 20 million board feet was set—the first known annual allowable cut calculation in the United States. Through the 150 years, there has been a priority for the sustainability of the forest. Even the most recent agreements between the tribe and the Federal government ensure that the forest will be sustained. The Trust and Management Agreement (MTE 1976) states that the goal for the Menominee Forest will be to manage for "quality and quantity of sawtimber material grown under sustained-yield management principles, while maintaining the diversity of native species."

The forest statistics indicate that the sustainability has been maintained. The estimated inventory in 1854 was 1.2 billion board feet, while the 1988 inventory estimates there are 1.7 billion board feet (Wilson 1994), while during the same period, 2.25 billion board feet were harvested. While these figures are impressive, there was a problem brewing. From the Continuous Forest Inventory (CFI), data trends were indicating that the forest was losing some of its diversity and moving towards a primarily northern hardwood cover type (table 1), especially in the 1979-88 measurement period. This was caused primarily through the use of single-tree selection management throughout the forest. Cover types like white pine and hemlock were losing acreage because of the invasion of tolerant hardwoods, primarily sugar maple. While this might be considered an acceptable alternative, not all of the sites are capable of growing high quality sugar maple.

The habitat type classification system (Kotar 1989) was used to identify the different sites on the forest. Based on key plant indicators, these eleven habitat types identify the site potential, including soil nutrients and moisture regimes. For each habitat type, certain tree species have been identified as species that will grow quality sawlog material as well as ones that will regenerate easily. These species are termed *featured species* or when grouped together they form *featured cover types*. Examples of these featured cover types for three habitat types are presented in table 2. As the forest habitat types are identified and mapped, the management objective for each stand can be determined. Stands that already were stocked with the featured species would be maintained. If a stand did not currently have any of these featured cover types present, they would be restored to one as soon as possible. The job was then to identify the proper silvicultural system that should be used to maintain or regenerate these featured species.

The TEAMS model (Wood 1988) developed by Northern Arizona University was selected to provide the acreage allocation and scheduling routines that would move the forest from its current condition to a desired legacy forest. Since the model solution is based solely on acreage, stocking and yields had to come from outside the model. In the past, the CFI was used for stocking, and growth estimations and yields were based on a cut/leave tally taken during the field measurements (Vandendriesche and Wilson 1992). There were little or no data to support the new management practices being proposed by the forestry staff. Simple growth and yield models did very little to provide potential stocking levels and to provide some sort of scheduling tool. The FVS model (Teck and others 1996) was selected to provide volume estimates that could be applied to the acreage from TEAMS/M. With its ability to simulate silvicultural prescriptions through the Event Monitor (Crookston 1990) system, it is proving to be the ideal tool. Each model will be discussed further followed by a discussion on the integration of the two models.

TEAMS/M Model

The TEAMS/M (Terrestrial Ecosystem Analysis and Modeling System /Menominee) is a hierarchical decision support system designed to provide managers with feasible and efficient possible paths for achieving both long-term and

Table 1—Cover type acreage trend, 1963-1988.

| Cover type | Acres by measurement year | | | |
	1963	1970	1979	1988
Red pine	2,728	1,736	3,226	5,460
White pine	15,388	17,622	19,359	16,629
Jack pine	3,474	3,474	2,234	744
Swamp conifers	22,337	22,584	22,089	21,344
Hemlock				
Hemlock	5,459	4,467	4,964	3,971
Hemlock-sugar maple	3,971	4,219	4,219	4,963
Hemlock-yellow birch	15,388	15,883	12,905	11,664
Hardwoods				
Sugar maple-beech	28,789	28,541	35,987	43,679
Mid-tolerant hardwoods	53,360	61,551	61,303	61,800
Red oak	3,475	4,220	4,714	5,957
Swamp hardwoods	2,731	2,977	2,481	1,985
Aspen/white birch	47,901	39,957	34,003	25,315
Pin oak	9,925	8,191	8,437	7,445
Temporary nonproductive	3,723	3,475	3,225	7,197
Permanent nonproductive	14,891	14,643	14,394	15,387
Total	233,540	233,540	233,540	233,540

Table 2—Example of featured forest cover type identification.

Habitat type	Featured forest cover types	Objective species	Associate species
AQVib	White pine Mid-tolerant hardwoods Red oak	White pine Red oak White ash Basswood	Red maple White birch Quaking aspen Pin oak White oak
AFAd	Sugar maple Mid-tolerant hardwoods Red oak	Sugar maple Beech Red oak White ash Basswood Hard & soft elm	Hemlock Yellow birch Hickory Quaking aspen
AH	Sugar maple	Sugar maple	Yellow birch Hickory White ash Red oak Basswood Hard & soft elm

short-term goals. The model consists of two hierarchical levels, Strategic and Tactical. The Strategic model identifies a general management strategy for achieving desired forest conditions at the end of the planning horizon (the Legacy Forest) while maintaining a relatively constant level of activity over the conversion period. Periodic activity is measured by acres treated. The Tactical model provides more detailed spatial and temporal information for the first 15 year period that is consistent with achieving strategic goals.

Both the Strategic and Tactical levels employ goal programming to identify preferred management strategies. At the Strategic level, the formulation is designed around a Model II harvest scheduling formulation based on area control method of forest regulation. Model II harvest scheduling is useful for planning the scheduling of multiple entries over the lengthy planning horizon (currently 150 years). Although Model II formulations can handle long time periods, they have the disadvantage that the on-the-ground identity of regenerated stands is lost in the final output. For this reason, another formulation is needed to develop a compartment-level harvest schedule.

The Tactical level uses a Model I formulation, which allows tracking of the harvest schedule to the level of specific compartments. Harvest treatments are assigned to cover types and habitat types within compartments, but not specific stands. The Tactical level employs mixed integer goal programming to develop an annual compartment level treatment schedule for the first strategic entry period (currently 15 years). It schedules compartments according to a pre-specified entry frequency such that the level of activity is approximately equal from year to year.

Cover type	TEAMS target acres	TEAMS solution	Difference TEAMS solution versus TEAMS target
			Percent
Red pine	8,300	8,300	100.0
White pine	39,750	39,750	100.0
Jack pine	1,000	100	10.0
Swamp conifer	21,500	20,281	94.3
Hemlock	10,400	10,400	100.0
Hemlock - sugar maple	5,800	5,885	101.5
Hemlock - yellow birch	11,150	11,150	100.0
Hemlock - total	27,350	27,435	100.3
Sugar maple	69,000	68,917	99.9
Midtol hardwood	21,040	21,809	103.7
Red oak	13,500	14,412	106.8
Swamp hardwood	1,000	328	32.8
Hardwoods - total	104,540	105,466	100.9
Aspen	10,000	10,000	100.0
Pin oak	3,000	3,000	100.0
Temporary nonproductive	2,000	1,875	93.8

Strategic Solution

The intent of this document is not to present a detailed analysis of the Strategic model solution. However, a brief discussion on the achievement of the legacy forest goals is quite important. While there are over 1,400 separate goals being solved for, the most important is how well would the implementation of the new management plan achieve the legacy forest goals. Table 3 provides a brief summary on how well each cover type did. Some cover types were deemed more important than other cover types and the model was designed to allow for this through the use of penalty weights. An example would be that it was very important that the white pine acreage were achieved while red pine was not. So the model ensures that the white pine acreage were reached before the red pine. A more detailed analysis of all the models goals is described in the "Forest Inventory Analysis: Implementation Plan" (Wilson 1997). For this paper, we will discuss in more detail the white pine cover type and its integration with the FVS model.

Cover Type Analysis

A good example on how TEAMS/M solves for a cover type is to look at the white pine cover type. White pine is an important cover type on the forest, and the inventory shows that there has been a 14 percent decrease in the acreage from its maximum of 19,359 down to 16,629 in 1988 (table 1). Through the use of the featured forest cover type process, it was identified that the forest could sustain about 40,000 acres of white pine. So one of the goals in the TEAMS/M model was to achieve this 40,000 acres in the legacy forest.

As mentioned in the previous section, a strategic level solution was generated that best met all of the goals set in the implementation plan. Part of that solution is detailed information on each cover type. The white pine cover type is presented in table 4, which shows the acres by age class at the end of each 15 year planning cycle. It should be explained here that the resulting white pine age class distribution is not the ideal, but was a conscience decision of the forestry staff after reviewing the results of different alternatives.

Table 4—TEAMS solution for white pine cover type. White pine acreage by period.

Year ending	Age										All Age	Total
	1-15	16-30	31-45	46-60	61-75	76-90	91-105	106-20	121-35	136-50		
Current	5,795.60	123.40	513.10	1,126.60	1,294.40	1,039.70	275.40	0.00	1,767.40	8,243.70	0.00	20,179.30
2012	8,530.30	5,795.60	123.40	513.10	1,126.60	1,294.40	1,039.70	275.40	0.00	6,511.10	0.00	25,209.60
2027	12,183.00	8,530.30	5,795.60	123.40	513.10	1,126.60	1,294.40	1,039.70	275.40	1,770.80	0.00	32,652.30
2042	2,782.40	12,183.00	8,530.30	5,795.60	123.40	513.10	1,126.60	1,294.40	1,039.70	280.00	0.00	33,668.80
2057	1,792.50	2,782.40	12,183.00	8,530.30	5,795.60	123.40	513.10	1,126.60	1,294.40	1,142.20	0.00	35,283.80
2072	2,782.40	1,792.50	2,782.40	12,183.00	8,530.30	5,795.60	123.40	513.10	1,126.60	750.80	0.00	36,380.40
2087	2,782.40	2,782.40	1,792.50	2,782.40	12,183.00	8,530.30	5,795.60	123.40	513.10	1,862.90	0.00	39,148.40
2102	1,854.80	2,782.40	2,782.40	1,792.50	2,782.40	12,183.00	8,530.30	5,795.60	123.40	677.90	0.00	39,305.10
2117	1,343.90	1,854.80	2,782.40	2,782.40	1,792.50	2,782.40	12,183.00	8,530.30	5,795.60	9.20	0.00	39,856.90
2132	3,974.90	1,343.90	1,854.80	2,782.40	2,782.40	1,792.50	2,782.40	12,183.00	8,530.30	1,735.60	0.00	39,762.70
2147	2,782.50	3,974.90	1,343.90	1,854.80	2,782.40	2,782.40	1,792.50	2,782.40	12,183.00	7,483.40	0.00	39,762.70

The alternative chosen was to regenerate all of the overmature white pine in a 40 year period and to do the restoration of non-featured cover types to white pine in the current rotation.

This solution provided the acreage basis that was used to determine the overall stocking and yields of the white pine cover type over the planning period. These acreage will be used later in this document when integrated with the FVS results.

FVS Model

The Menominee forestry staff was introduced to the FVS model in April, 1996. The Lake States TWIGS Variant (Bush and Brand 1995) had just been developed and was ready for use. After an introduction to the model by Richard Teck of the U.S. Forest Service and Don Vandendriesche of the Bureau of Indian Affairs, the general consensus was that the model had possible application to the problem at hand. Work began immediately to develop event monitor keyword files for the prescriptions being used for management of the featured forest cover types. Data was prepared from the CFI data base for use in the model.

CFI Data Base

On the Menominee Forest, there is a set of permanent CFI plots that are used in the management and planning of all forest activities. The CFI has been measured four times—in 1963, 1970, 1979, and 1988. For each of the 884 plots that are actually measured, data were collected on individual trees for each plot. Each plot was stratified by management potential, based on the featured forest cover type principles. These strata would then be processed through FVS and the FVSSTAND model (Vandendriesche 1997) to create stocking and yield data tables.

First, the CFI data were used to calibrate the FVS model. As a stand-alone model, Lake States TWIGS Variant (Miner and others 1988) has its limitations, especially on a unique forest like Menominee. But when integrated into FVS with its capabilities to locally calibrate the growth and yield equations, its limitations were overcome. The CFI was then used to calibrate the READCORD, MCDEFECT and BFDEFECT keywords.

The CFI data were also used to calculate ingrowth data for the FVS model. Since the FVS - Lake States TWIGS Variant does not contain natural regeneration/ingrowth algorithms, estimates of ingrowth were calculated for each age class. The CFI plots from all three measurement intervals were analyzed and average trees per acre per age class were calculated and incorporated into the simulation using the NATURAL keyword. An abbreviated example of the white pine cover type ingrowth using the NATURAL keyword is presented in figure 1. While only three age classes are presented, values were entered for each age class for the entire rotation.

FVS Procedures

The FVS model was integrated into the Menominee CFI software (Vandendriesche 1997) for automatic analysis by

```
IF            0
AGE EQ   40
THEN
ESTAB
NATURAL       0   BF    1    100   10   12   0
NATURAL       0   WC   14    100   10    8   0
NATURAL       0   EH    4    100   10   11   0
NATURAL       0   RM    5    100   10   18   0
NATURAL       0   SM    2    100   10   15   0
NATURAL       0   PB    2    100   10   14   0
NATURAL       0   QA    6    100   10   14   0
NATURAL       0   BC    3    100   10   15   0
NATURAL       0   PN    5    100   10   12   0
NATURAL       0   RO    1    100   10   18   0
NATURAL       0   RE    1    100   10   14   0
END
ENDIF
IF            0
AGE EQ   50
THEN
ESTAB
NATURAL       0   BF    1    100   10   14   0
NATURAL       0   WS    1    100   10   10   0
NATURAL       0   EH    1    100   10    9   0
NATURAL       0   RM    6    100   10   14   0
NATURAL       0   AB    1    100   10   15   0
NATURAL       0   QA   11    100   10   17   0
NATURAL       0   BC    1    100   10   10   0
NATURAL       0   RO    1    100   10   22   0
END
ENDIF
IF            0
AGE EQ   60
THEN
ESTAB
NATURAL       0   BF    2    100   10   19   0
NATURAL       0   WP    8    100   10   15   0
NATURAL       0   WC    1    100   10    4   0
NATURAL       0   EH    4    100   10    8   0
NATURAL       0   RM   10    100   10   15   0
NATURAL       0   SM    2    100   10   13   0
NATURAL       0   PB    3    100   10   16   0
NATURAL       0   BT    2    100   10   21   0
NATURAL       0   QA    4    100   10   23   0
NATURAL       0   BC    2    100   10   14   0
NATURAL       0   RO    2    100   10   10   0
END
ENDIF
```

Figure 1—Example of ingrowth records.

the forestry staff. The Bureau of Indian Affairs has developed a menu of different programs that allow for the selection of any CFI plot strata. Each plot has an individual keyword file that is created that has basic FVS parameters set for the strata. Incorporated in this keyword file is a call to open another keyword file which contains the management prescription. The plot data are retrieved from the data base and a batch file is created to execute FVS.

After the plots are processed, FVSSTAND is executed to build a summary file for the selected strata. FVSSTAND is a new program that works with each tree file and builds a summary by either age classes or time periods, depending on the cover type management. FVSSTAND generates stocking and yield summary tables for the total stand, along with species groups. These summary data were what was used in the integration with TEAMS/M. The stocking and yield data for the white pine cover type, by age class are presented in tables 5 and 6.

Model Integration

It is the integration of both models which provides valuable information on the results of the management strategy. The age class acreage developed in table 4 were merged with the stocking results presented in table 5. The resulting table provides an estimate of the stocking for the white pine cover type over the next 150 years. As shown the estimated volume will increase from a current estimate of 314 to 762 million board feet in 150 years (table 7). Along with the realization that the model is ecologically based, this helps assure the

Table 5—White pine cover type stocking volumes per acre.

Age class	Basal area	Cubic foot	Board foot
1 - 15			
16 - 30			
31 - 45	93	1,839	4,246
46 - 60	129	3,043	9,941
61 - 75	154	3,539	11,717
76 - 90	154	3,829	15,087
91 - 105	164	4,273	19,177
105 - 120	165	4,417	21,553
121 - 135	162	4,460	23,564
136 - 150	171	4,693	27,141

Table 6—White pine cover type yield volumes per acre.

Age class	Basal area	Cubic foot	Board foot
1 - 15			
16 - 30			
31 - 45	7	150	14
46 - 60	63	1,388	219
61 - 75	45	1,130	1,161
76 - 90	44	1,153	4,070
91 - 105	42	1,160	5,086
105 - 120	35	998	5,102
121 - 135	31	897	4,921
136 - 150	25	773	4,498
1st Cut	77	2,227	14,385
2nd Cut	64	2,061	13,203
3rd Cut	32	1,998	6,756

elected officials that the management practices will do what is intended.

As for yields, the TEAMS/M model provides the acreage by period that will be regenerated. In our example, we know how many acres of white pine that will be regenerated during each period. Using the FVS model yield summaries (table 5), the estimated yield volume from management can be calculated. By determining the remaining acres in the white pine cover type that are not being regenerated, the

estimated acres available for thinning can be calculated. Again, the total thinning volumes are calculated from these thinning acres multiplied by the yield estimations coming from the FVS model. The total yields for the white pine cover type over the planning period can be reported separately and then combined with all other cover types for total yield estimations.

Conclusions

The FVS model and TEAMS/M model are proving to be invaluable tools for forest management planning on the Menominee Reservation. But it is the combination of the two that has made the difference in the planning process. Allocating and scheduling acreage under a hierarchical planning strategy provides the forestry staff the information in determining the proper strategy for reaching the legacy forest. By developing a strategic model first, it has allowed the staff to determine the long-range plans needed to enhance the forest, instead of having the staff bogged down by details of individual stands.

While the FVS simulations are still being evaluated, the preliminary results indicate that results are valid and can be integrated into the TEAMS/M analysis. Keyword files are providing a new avenue for providing immediate analysis for the many different management options being considered in the forest management operation. Better and accurate growth and yield data can be immediately generated with this model, giving the staff the information that was not available in the past.

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Table 7—Total stocking volumes, white pine cover type, by period.

Year ending	1-15	16-30	31-45	46-60	61-75	76-90	91-105	106-20	121-35	136-50	Total
						Thousand board feet					
Current	0	0	2,179	11,203	15,167	15,686	5,282	0	41,650	223,741	314,909
2012	0	0	524	5,103	13,200	19,529	19,938	5,937	0	176,717	240,949
2027	0	0	24,608	1,227	6,012	16,998	24,883	22,409	6,491	448,062	150,630
2042	0	0	466	57,632	1,446	7,742	21,605	27,899	24,500	7,600	148,890
2057	0	0	665	14,275	67,905	1,862	9,840	24,282	30,503	31,001	180,333
2072	0	0	152	20,387	85,769	87,440	2,367	11,060	26,548	20,377	254,100
2087	0	0	98	4,656	18,023	48,123	259,229	223,948	136,571	250	690,951
2102	0	0	152	3,000	27,977	210,704	181,506	124,910	2,909	18,401	569,558
2117	0	0	152	4,656	18,023	48,123	259,229	223,948	136,571	250	690,951
2132	0	0	101	4,656	27,977	31,001	59,205	319,844	236,289	47,106	726,181
2147	0	0	73	3,104	27,977	48,123	38,141	73,050	337,471	234,422	762,360

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The Ecosystem Diversity Matrix Projection System: A Visualization Tool for Ecosystem Management

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Abstract—Currently there are numerous efforts under way to develop resource management tools that address the objectives of ecosystem management. The Ecosystem Diversity Matrix (EDM) Projection System is one of these tools. The EDM Projection System is an interactive visualization tool that allows technical and lay audiences to visualize existing landscape conditions and explore how forest management decisions will impact future forest health and diversity. The projection system uses FVS and a graphical display system to project and display forest acreage movements over time through the Idaho Southern Batholith Ecosystem Diversity Matrix. The EDM is displayed as a frequency bar chart depicting acreage distributions across a matrix of habitat type group and vegetation structural stage combinations. Four management prescriptions representing a range of management goals allow the user to interactively explore how management decisions will impact the landscape. In addition to displaying acreage distributions, the program is designed to display time-series charts of ecosystem outputs and attributes such as ecosystem diversity, forest risk ratings, habitat suitability, harvest volumes, and economic returns.

Today there are many different agencies, organizations, and private companies proposing various strategies for implementing and addressing the objectives of ecosystem management. In 1994, Boise Cascade Corporation initiated the Boise Cascade Idaho Ecosystem Project to formulate an ecosystem management strategy for the 5.8 million acre Idaho Southern Batholith landscape in west-central Idaho. To participate effectively with multiple owners in the Batholith landscape, the project staff identified that one of the most critical first steps in developing a resource management strategy for ecosystem management was to develop an ecological land classification system that is compatible with all landowners.

With this understanding, the project staff along with project partners developed an ecological land classification system described as the Ecosystem Diversity Matrix. The Ecosystem Diversity Matrix is a tool that incorporates an existing ecological land classification system, habitat typing, and a forest succession temporal component for describing vertical forest structure. The Ecosystem Diversity Matrix concept is based on work by Haufler (1994). The Ecosystem Diversity Matrix classifies forest acreages according to habitat type groups and vegetation structural or growth stages as shown in table 1. Each unique combination of habitat type group and vegetative growth stage is referred to as an "ecological land unit," or ELU. ELU's describe the existing forest community with regard to overstory/understory vegetation, and vertical forest structure (for example, single-story versus multi-story). In addition, since the ELU definition is based on habitat type, the productivity of the site can be quantified, as can potential long-term successional pathways. Also, potential stand hazards, and potential shrub species can be associated with each ecological land unit.

Within the context of a geographic information system (GIS), ELU's can be mapped across a landscape as the intersection of a habitat type "layer" and a vegetation growth stage "layer." When ELU's are mapped across an entire landscape, and subsequently summarized via the Ecosystem Diversity Matrix, the EDM becomes the framework for quantitatively characterizing regional ecosystem diversity; it provides a basis for assessment of wildlife habitat quality; it quantifies the contributions of ecosystem diversity by all landowners; and it forces planners to recognize the dynamic nature inherent in ecosystems.

With the development of the Ecosystem Diversity Matrix framework in place, the project staff set out to develop a tool that would project the existing classified EDM landscape into the future. This tool became known as the Ecosystem Diversity Matrix Projection System. The goal of the projection system was to provide a means to visually display a

Table 1—Simplified ecosystem diversity matrix populated with acres by ecological land unit.

Vegetation growth stage	Habitat type group			
	Pine	Douglas-fir	Grand fir	Alpine fir
Seedling	100	100	500	
Sapling		100		
Small tree		100	50	
Medium tree		100		200
Large tree		100	300	200
Total acres	100	500	850	400

multitude of ecosystem attributes and outputs over time under various management regimes in a simple, concise format. The system was to rapidly evaluate the overall affect of a set of management options on future forest health and ecosystem diversity. And finally, the projection system was to be easily understood by technical and lay audiences to facilitate ecosystem management discussions.

The Ecosystem Diversity Matrix Projection System displays three-dimensional bar charts of ecosystem acreage distribution across the Ecosystem Diversity Matrix. The current ecosystem acreage distribution can be displayed, as well as the projected acreage distribution at 10 year increments for the next 100 years. By comparing acreage distributions at current and future time periods, the user can easily see the overall affect of management on future ecosystem diversity (fig. 1).

The technique used to project future acreage distributions within the EDM Projection System relies heavily on the Forest Vegetation Simulator: FVS (Stage 1973; Teck and others 1996; Wykoff and others 1982). FVS was used to simulate the development of a wide range of stands within the study area. The results of these FVS simulations were then summarized into a set of databases that link to the projection system and define how acreages move through the matrix over time.

The Ecosystem Diversity Matrix Projection System is a Windows-based application written in Visual Basic. The program utilizes Graphics Server software to generate three-dimensional charts, and utilizes an Excel spreadsheet to store and compute various program variables (Visual Basic, Windows, and Excel are registered trademarks of Microsoft Corporation, Graphics Server is a registered trademark of Pinnacle Publishing).

How the Ecosystem Diversity Matrix Projection System Works _____

The EDM Projection System graphically depicts current and projected ecosystem diversity via the Ecosystem Diversity Matrix. A matrix of existing ecological land unit (ELU) acreages classified according to the EDM is projected through time under user-selected management options using pre-computed transition probabilities. These transition probabilities were developed from the results of extensive FVS simulations run on a wide range of stands within the study area. The transition probabilities define how acreages in each cell of the EDM matrix will transfer to other possible cells within a habitat type group over a 10 year time period, under a given management option.

It is the use of these pre-computed transition probabilities, based on extensive FVS simulations, that allows the EDM Projection System to rapidly evaluate the overall landscape affects of different management alternatives. This ability to rapidly evaluate management alternatives is essential to the intended use of the EDM Projection System.

Four pre-defined management alternatives are incorporated into the EDM Projection System. The four alternatives span a range of management intensities; from no active management to intensive silvicultural treatment. The user specifies what proportion of the landscape is to be managed according to each of the four management scenarios. The transition probabilities that define how acreages move through the Ecosystem Diversity Matrix are specific to each management alternative. By changing the mix of prescriptions applied to the landscape, the user can visualize the affect of forest management decisions on future forest health
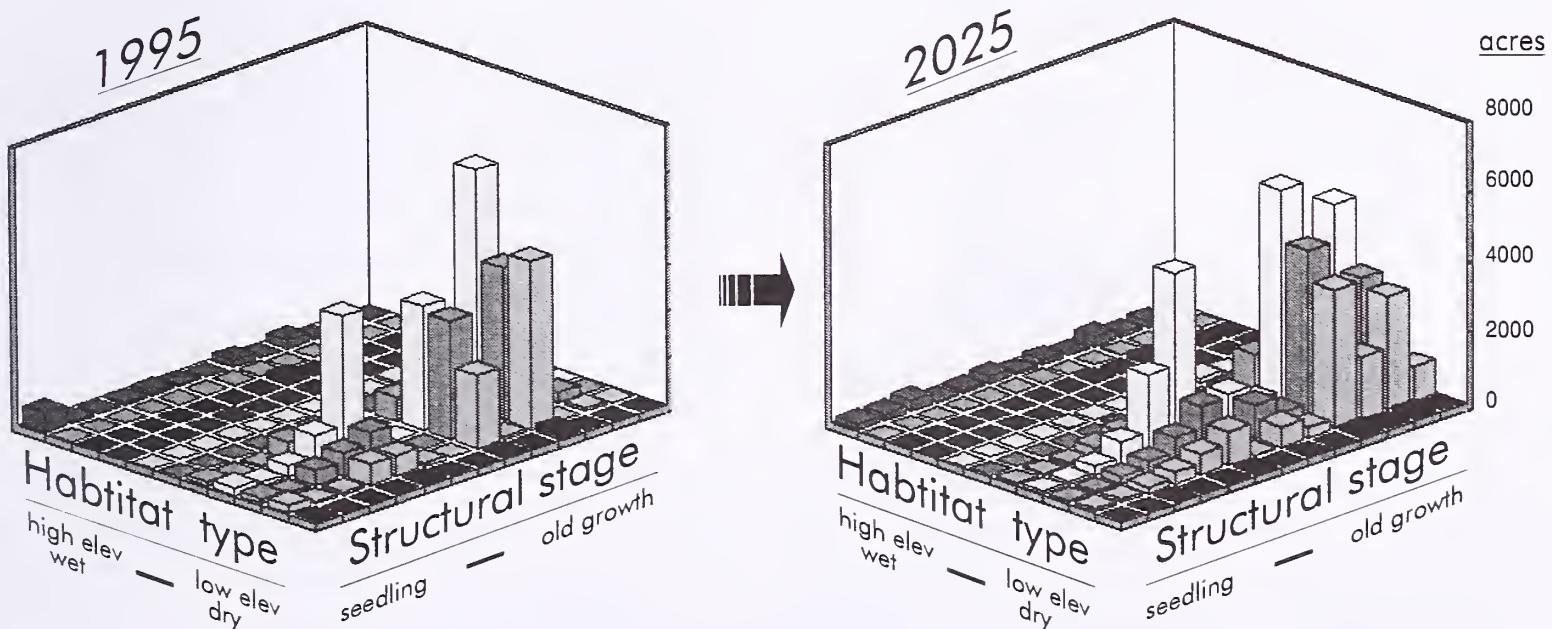
Figure 1—Simplified, conceptual view of the EDM projection system function.

and diversity, via the EDM acreage distribution graph and the time-series graphs.

The primary display in the EDM Projection System user interface screen is a three-dimensional bar chart showing forest (ELU) acreage distribution across the matrix of habitat type groups and vegetation growth stages. The user specifies what time period is displayed in the acreage distribution graph. The user may display the initial acreage distribution, or projected acreages at any of 10 subsequent 10 year time intervals.

Several time series indices depicting various stand attributes/outputs are also included in the EDM Projection System display. These graphs show the trend of various ecosystem attributes and outputs over time, under the specified management alternatives. Five small windows along the bottom of the interface screen display user-specified time series graphs such as "harvest volume" or "acres at risk" (fig. 2). The source for the values displayed via the time-series charts is the same FVS simulations that were run to generate the EDM transition probabilities. Values for harvest volumes, risk ratings, habitat suitability ratings, and so forth, were generated during these simulations. These ecosystem outputs/attributes were then summarized, by ELU, by management alternative, and stored in a set of databases. These databases are linked to the projection system and provide the data necessary to drive the time-series charts.

Computing EDM Projection System Transition Probabilities

Transition probabilities were developed for the EDM Projection System that define, for a given habitat type group, how acreages in each vegetation growth stage will transfer to other vegetation growth stages over a 10 year time period, under each of four possible management prescriptions. These transition probabilities were derived from extensive forest growth projections made using Boise Cascade's Central Idaho variant of the FVS model (Boise Cascade Corporation 1994, 1997). Data for the stand projections came from Boise Cascade's Central Idaho Timberlands Continuous Forest Inventory system, and from Boise Cascade's Idaho Ecosystem Management Project. Approximately 900 stands were simulated, under four different management alternatives, over a 200 year projection period, to develop the transition probabilities.

FVS keyword files for simulating forest growth under the four different management prescriptions were developed. The simulation horizon for each management prescription was twenty 10 year time periods. The regeneration establishment model (Ferguson and Crookston 1991) was invoked to simulate natural regeneration over the course of the stand growth projections. Record tripling was activated in the simulations to add random tree variation; no insect or
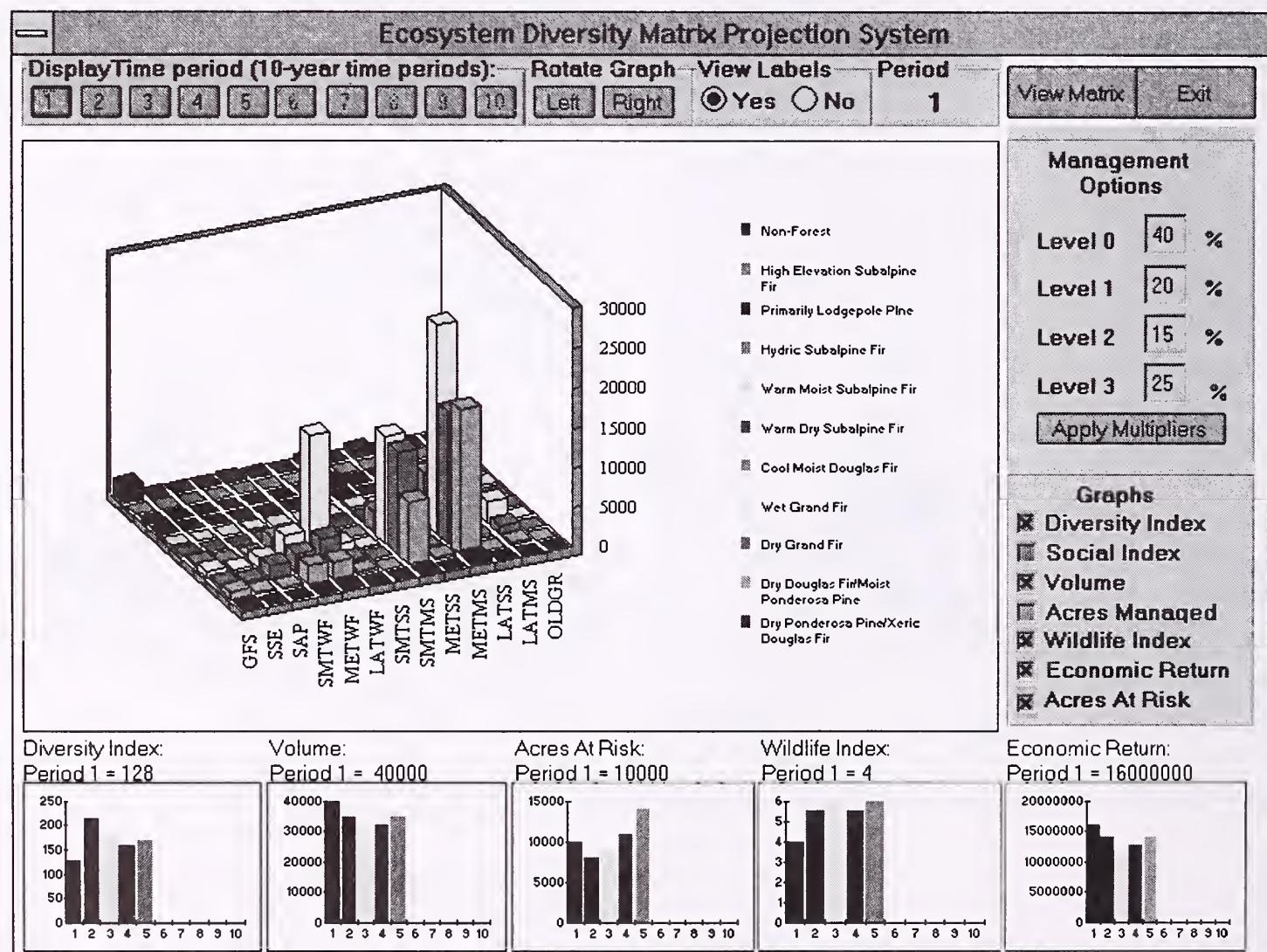
Figure 2—The EDM projection system interface screen.

disease extensions were invoked for any of the four management prescriptions.

At each cycle in the growth simulations, the stand was classified according to the ELU classification system using an algorithm described by Warren and others (1997). The ELU classification system classifies stands into 37 different vegetation growth stages and 12 different habitat type groups (table 2). This classification logic is built into Boise Cascade's Central Idaho variant of the FVS model, but the same logic is also available as a FVS post-processor.

This use of a stand growth and yield simulator to quantify future forest vegetation structure is similar to work done by Barrett and others (1994), and Stage and others (1995).

Transition probabilities were computed using the results of the FVS simulations discussed above. The end result of post-processing outputs from the simulations was a database of paired observations that indicated each stand's ELU classification at time "T", and 10 years later at time "T + 1". Using this database of paired observations, transition probabilities could be computed that indicated the proportion (probability) of stands moving from one ELU category to another over a 10 year time period. These probabilities are specific to each of the four pre-defined management prescriptions available in the EDM Projection System. The management prescriptions are discussed in the following section; the computation and application of transition probabilities is illustrated by the example in figures 3 and 4.

Since acres cannot move from one habitat type group to another within the EDM, the transition probabilities need

	Vegetation growth stage at period (T+1)		
Vegetation growth stage at period T	Small trees, single story, low density	Small trees, single story, med density	Med trees, single story, med density
Small trees, single story, low density	2 stands	2 stands	1 stand
Resultant EDM cell transition probabilities	2/5=0.40	2/5=0.40	1/5=0.20

Figure 3—Example computation of EDM transition probabilities.

	Transition probabilities for: vegetation growth stage at period (T+1)		
Vegetation growth stage at period T	Small trees, single story, low density	Small trees, single story, med density	Med trees, single story, med density
Small trees, single story, low density	0.4	0.4	0.2

Acres at time period T:

100.0	0.0	0.0

Acres at time period T+1:

40.0	40.0	20.0

Figure 4—Example application of EDM transition probabilities.

Table 2—Vegetation growth stages and habitat type groups used in the EDM projection system.

Vegetation growth stages	Densities
Grass, forbs, seedlings	
Shrub/seedling	Low/med/high
Sapling; shrub/seedling	Low/med/high
Small trees; multi-story; with past fire	Low/med/high
Medium trees; multi-story; with past fire	Low/med/high
Large trees; multi-story; with past fire	Low/med/high
Small trees; single-story	Low/med/high
Medium trees; single-story	Low/med/high
Large trees; single-story	Low/med/high
Small trees; multi-story	Low/med/high
Medium trees; multi-story	Low/med/high
Large trees; multi-story	Low/med/high
Mature forest	Low/med/high

Habitat type groups

Dry ponderosa pine/xeric douglas-fir
Dry douglas-fir/moist ponderosa pine
Dry grand fir
Cool moist grand fir
Cool dry Douglas-fir
Cool moist Douglas-fir
Warm dry subalpine fir
Warm moist subalpine fir
Hydric subalpine fir
Persistant lodgepole pine
High elevation subalpine fir
Non-forest

only define how the acres move from one vegetation growth stage to another within a habitat type group (column) of the EDM. Even so, the number of transition probabilities is large. Transition probabilities were required for describing acreage movements between each of the 37 different vegetation growth stages (table 2), for each of 12 habitat type groups (table 2), under each of four management prescriptions. The total number of transition probabilities then is 37*37*11*4 = 60,236. A large proportion of these transition probabilities are zero since there is little chance of numerous transitions ever occurring (for example, a stand in a "seedling" growth stage growing into an "old growth" stage within a 10 year time period).

Management Prescriptions Available in the EDM Projection System

Four management prescriptions of varying intensities were developed for the EDM Projection System. These four management options were selected to represent the broad range of potential management prescriptions that are being considered for the Idaho Southern Batholith. The four alternatives span a range of management intensities; from no active management to intensive silvicultural treatment. The user specifies what proportion of the landscape is to be managed according to each of the four management scenarios.

It is important to note here that these prescriptions are applied proportionally across the entire landscape and in no way should they be viewed as site-specific prescriptions. As such, the resulting landscape conditions projected in the projection system represent only potential "what if" projections of ecosystem diversity and forest health for the entire 5.8 million acre landscape.

The four pre-defined management scenarios available in the EDM Projection System are as follows:

No Management Prescription: The no management prescription depicts the natural growth and mortality of a stand in the absence of any active management. This prescription was selected to evaluate its impact across the landscape if no management activities were to occur.

Fuel Reduction Management Prescription: This management prescription was selected and designed to represent management actions that are necessary to reduce the quantity of ladder fuels and return to the more historical fire-driven open park-like conditions that existed in west-central Idaho. The fuel reduction prescription is basically a thin from below to a target basal area (that is: reduce the basal area in smaller trees). Over the course of the simulation, the event monitor (Crookston 1990) was used to maintain forest stocking within set basal area limits. This is one of the management options that the U.S. Forest Service is considering to reduce the quantity of ladder fuels and reintroduce prescribed fire back into the ecosystem.

Economic Management Prescription: The economic management prescription was selected to represent a management alternative that would maintain forest health by reducing risk from wildfire, insects and disease, and produce a sustainable flow of income to local economies. This prescription incorporates a continuous selection harvest scenario with a return or re-entry time of 15 years. The selection harvests or thinnings favor removal of large, poor crown, defect trees with a thinning residual of 50 square feet of basal area (an accepted target residual basal area for forest industries in west-central Idaho).

Accelerated Management Prescription: The accelerated management prescription uses intensive silvicultural techniques to maximize fiber growth, reduce forest health risk, and return forest stands back to a representation of their historical fire-driven open park-like condition. The intent of this prescription is to examine how we can use more intensive silviculture to reach a desired forest structure

condition. The prescription invokes a thinning from below when the stand reaches a trigger basal area. The prescription thins the stand to a set residual basal area, favoring retention of shade-intolerant species and good crown ratios. A tree removal ranking logic was established to favor intolerant species, good crown ratios, and larger diameter trees. This ranking along with the basal area targets are evaluated with the event monitor in each time period throughout the simulation.

Time Series Indices

For the user-specified time period, the Ecosystem Diversity Matrix Projection System displays a three-dimensional bar chart of ecosystem acreage distribution across the Ecosystem Diversity Matrix, resulting from the user-specified mix of management alternatives. The current ecosystem acreage distribution can be displayed, as well as the projected acreage distribution at 10 year increments for the next 100 years.

In addition, the EDM Projection System also allows the user to select a number of time series graphs that show the trend of selected ecosystem attributes and outputs over time. The intent of the time series graphs is to provide some relative indexes that measure how change associated with different management options occurs across the entire landscape. Because these are indices and relative measures, they are intended only to illustrate general trends across the landscape and not specific outcomes.

Currently, the EDM Projection System provides indices that measure ecosystem diversity, risk ratings, habitat suitability for selected species of concern, harvest volumes, economic returns, and quantity of acres managed in the Idaho Southern Batholith landscape. Each of these indices are displayed below the EDM acreage display as simple time-series bar charts over time (fig. 2). Based on the selected mix of management options, the user can interactively observe how each of these indices change over time and evaluate broad landscape scale results of management decisions.

The source for the values displayed via the time-series charts was the FVS simulations that were used to generate the EDM transition probabilities. Values for harvest volumes, risk ratings, habitat suitability ratings, and so forth, were generated during these simulations. These ecosystem outputs/attributes were then summarized, by ELU, by management alternative, and stored in an Excel spreadsheet. This spreadsheet is linked to the projection system and provides the data necessary to drive the time-series charts.

Conclusions

The Ecosystem Diversity Matrix Projection System is a promising and exciting tool for visualizing ecosystem management strategies at the landscape scale. It allows technical and lay audiences to visualize a host of ecosystem attributes and outputs over time while allowing them to set the management option prescriptions for the entire landscape. As such, it is a visualization tool that all end users from politicians to scientists to the general public can use to

examine how forest management decisions can potentially impact ecosystem diversity, productivity, and risk both for today and into the future.

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Individual Stand Projection Under Different Goals to Support Policy Analysis for the Sierra Nevada Ecosystem Project

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Abstract—The Sierra Nevada Ecosystem Project (SNEP) was commissioned by Congress to assess the health of the ecosystems of the Sierra Nevada and to evaluate management strategies to maintain the health and sustainability of these ecosystems while providing resources to meet human needs. As part of this effort, a policy analysis model was developed to analyze the ecological and economic implications of alternative strategies for managing late successional forests in the Sierra Nevada. To understand the implications of different management strategies, it was necessary to project forest characteristics, ecological effects, timber yields, and costs and revenues for each forest stratum under different goals. This paper describes the methodology for managing individual stands to achieve the goals associated with the strategies. Using the growth and yield simulator FVS for forest growth projections, a goal-oriented dynamic programming approach was developed to identify efficient prescriptions to reach alternative forest structure targets. This effort included natural disturbance in the prescription generation. These prescriptions were then passed to a policy analysis model to be drawn upon to meet overall forest goals for alternative management strategies.

The Sierra Nevada Ecosystem Project (SNEP) was commissioned by Congress to assess the health of the ecosystems of the Sierra Nevada and to evaluate "management strategies to maintain the health and sustainability of these ecosystems while providing resources to meet human needs (SNEP 1994)." The bill also requested that ecological, timber harvest, economic, and social effects of the alternative management strategies be specified.

Assessment of Sierra Nevada ecosystems has revealed a number of problems with achievement of health and sustainability (SNEP 1996) including: (1) decline in the amount and complexity of late-successional forest in the commercial forest types, especially mixed conifer and east-side pine, (2) declines in aquatic biodiversity and existing and potential threats to riparian-associated species, and (3) existing and potential difficulties from watershed disturbance. Also, it appears that there may be increased threat of severe fire in some forest types from the build-up in fuels and decrease in fire periodicity, although opinions vary about the degree of that increase. Franklin and Fites-Kaufmann (1996) have proposed and evaluated the potential for a number of different conservation strategies for late-successional forests. These conservation strategies all increase the general extent and complexity of late successional forests in the Sierra, with varying degrees of human intervention through prescribed fire and mechanical treatment (timber harvest and road building) to accelerate development of late-successional characteristics and reduce the threat of fire. For the late-successional analysis, Franklin divided the Federal lands of the Sierra Nevada into late-successional old-growth (LSOG) polygons based on the characteristics of the forest. These average approximately 2,500 acres in size.

To understand the implications of different late-successional policies, Sessions and others (1996) project forest characteristics, ecological effects, timber yields, and costs and revenues for each stratum within each LSOG polygon where management of the stratum is directed toward achieving the goals of the policies. As part of that analysis, they simulate large-scale fires on the landscape and the resulting effects.

Methods

The methodology described in this paper has three major components, all focused at the stratum level: (1) projecting stratum characteristics through time using a set of growth relationships, (2) linking stratum conditions and activities at each point in time to ecological conditions and effects, and (3) deciding the actions to undertake over time to move the stratum toward specified goals. The term stratum refers to a grouping of non-contiguous, and relatively homogenous forest structures. A stratum is described by the biometrics of the average acre within. The term stand is typically used to describe a contiguous subset, in other words a definable polygon, of a stratum.

The primary objective of this analysis is to be able to guide stand development over time toward specified goals. Also we wish to know the resulting yields, costs, revenues, and ecological effects. In this analysis, different types of activities are considered such as timber harvest and prescribed burning. To consider these activities over time, we build "prescriptions" that portray a combination of activities over time and the associated conditions, outputs, and effects. To derive prescriptions for use in the analysis of different conservation strategies for late-successional forests, the FVS Prescription Generation Model was developed. FSVPGM is a per acre level multiple-objective simulation heuristic

that uses a set of silvicultural and ecological goals as the drivers controlling stand development. The model searches for solutions that lead to the development of stand structures most closely meeting specified silvicultural and ecological goals. The per acre based combinatorial search procedure used in FVSPGM combines a dynamic programming search algorithm using the PATH procedure (Cousar and Brodie 1992; Paredes and others 1987; Yoshimoto and others 1990) with a goal programming style objective function to minimize deviations from silvicultural and ecological goals for a single stand.

Growth Relationships

The search algorithm uses the single stand growth and yield model FVS to project stand growth (Stage 1973). The specific variant of FVS, WESSIN, used in our simulations is the version calibrated for the west side of the Sierra Nevada (Dixon 1994). We have chosen FVS because of its availability, its recent calibration for the Sierra Nevada, and its ability to simulate growth and yield effects for the types of management actions we plan to evaluate. It may be appropriate in future studies to revisit the choice of simulation model as locally calibrated gap models become available (see, for example, Botkin and others 1970; Burton and Urban 1990). This is particularly true if the study interest includes forest succession under climate change, silvicultural prescriptions other than individual tree selection, and increased interest in understory development other than trees.

Ecological Linkages

The SNEP policy group, in coordination with the SNEP work groups responsible for assessing late successional forests, wildlife diversity, watershed health, and natural disturbance in the Sierra Nevada, has adopted a set of indices for linking ecological response to vegetation change. These indices are calculated from stand structure attributes at any point in time including tree species, size and number, canopy closure, snags, and size and number and the height to the live crown by diameter class and species. The specific ecological and watershed health indices are late successional-old growth (LSOG) rank (Franklin and Fites-Kaufman 1996), Wildlife Habitat Relationship (WHR) class (Airola 1988), and fire hazard (Bahro 1996).

A system developed by Franklin and Fites-Kaufmann (1996) classifies a stand into one of six ranks 0-5, with 5 signifying the largest contribution to late-successional characteristics and 0 signifying the lowest contribution (table 1). The ranking depends upon the number of large trees greater than a minimum diameter at breast height (d.b.h.), total canopy, and intermediate canopy closure. Because of uncertainty in the modeling of large tree mortality and snag decay and fall down rates, snags were not included in determining LSOG rank in the final analysis.

Linkages of stand condition to natural disturbance such as fire and disease have also been developed. Models linking the intensity of forest fires and stand condition were developed by Rothermel (1983). These models use fuel at the ground level, and topographic and weather conditions to predict the flame length of the advancing fire front. Relationships have also been derived to express the probability of fire moving up into the crowns of trees as a function of flame length, height to the live crown, and foliar moisture (Alexander 1988). Stand conditions under which fire can carry through the crowns of trees have been examined by Van Wagner (1977) and Agee (1993). The probability of individual tree death as a function flame length, expressed as scorch height, species, and tree diameter have been incorporated into the First Order Fire Effects Model (FOFEM) developed by the U.S. Department of Agriculture, Forest Service (Reinhardt and others 1997).

Simulated Strategies

Prescriptions are developed for each of six different forest management strategies. Four of the six strategies are based upon goals for the late successional old growth (LSOG) rank of the stratum; these are:

1. Matrix - Rank 2
2. Matrix - Rank 3
3. ALSE - Rank 3
4. ALSE - Rank 4.

Table 1—Summary of criteria to determine late successional old growth rank in westside and eastside mixed conifer and ponderosa pine strata types.

LSOG	Large tree	Min # trees	Min canopy	Min intr. canopy	Snags
Rank	D.b.h.	Per acre	Percent	Percent	Per acre
5	40	10	55	10	2.0
4	40	6	40	0	2.0
4	40	2	55	10	2.0
4	30	12	55	0	0.5
3	40	6	20	0	0.5
3	40	2	40	0	0.5
3	30	6	40	0	0.5
2	40	2	20	0	0.0
2	30	2	20	0	0.0
2	24	20	40	0	0.0
1	30	0.5	10	0	0.0

The terms Matrix and ALSE (Areas of Late Successional Emphasis) refer to different land allocations in the policy analysis of alternative conservation strategies for late-successional forests. ALSE areas are LSOG polygons that emphasize the maintenance and restoration of late successional forests in the Sierra under some conservation strategies. An important goal of the ALSE strategies is the reduction of fire hazard. ALSE prescriptions permitting harvest include "biomass removals" during harvest if necessary to eliminate fuel ladders, crown density reductions to reduce the risk of crown fire, and slash treatment. Prescribed burning is also permitted to reduce fuel loadings.

Matrix areas are the remaining area outside ALSEs. "Rank" refers to the Franklin and Fites-Kaufmann (1996) classification for contribution to late successional forest structure. The matrix goals allow for the harvest of large trees surplus to the rank goals; the ALSE goals do not. In terms of the structural goals, the ALSE strategies require higher stocking of large trees and denser canopies.

The other two strategies are:

5. Minimize fire hazard
6. Maximize present net value

The fire hazard strategy attempts to find a set of actions through time that minimize a fire hazard index considering potential flame length, stand crown closure, and basal area loss from fire. It includes commercial harvest, prescribed burning and biomass in the harvest, in other words the harvest of small material that reduces fire hazard but ordinarily would not be removed in a commercial sawlog operation.

The present net value strategy attempts to find a set of actions through time that maximizes the present net value of the stand, specifically, the value of the timber harvest over time and the value of the residual stand at the end of the planning horizon.

Range of Activities Evaluated

For each of the above management strategies, one of five potential types of "activities" can take place in each period. Three are initiated by human action: prescribed fire (P), development of a defensible fuel profile zone or fuel break (B), and timber harvest through thinning and partial cutting (H). Two other "activities" are also considered: wildfire (F) and no action (N). A series of five activities (one per 10 year period) defines the activity set over a planning horizon.

The five potential activities possible represent over 3,000 activity combinations for each strategy over the five periods (5^5). For example, "NNNNN" would involve no activity throughout the planning horizon, the activity set "HNHNH" involves a potential harvest in periods 1,3,5, and the activity set "FNNNN" represents a wildfire occurring under extreme fire conditions in period 1, and no activity in periods 2 through 5.

To reduce the number of combinations, a set of 17 rules were developed that govern the creation of the combinations, to a maximum of 324 possible activity combinations. Two examples of the rules: (1) a fuel break can only be initially developed in the first or second period; (2) harvests can occur, at most, every other period on steep slopes. FVSPGM calculates the resulting volumetric, biometric, and ecological outputs that are attainable and most closely meet the silvicultural and ecological stand goals over time for each activity set.

FVSPGM Modeling

Progress towards a silvicultural/ecological strategy is measured through nine modeling goals that describe stand structure: (1) large trees, (2) total canopy closure, (3) intermediate canopy closure, (4) snags, (5) down wood, (6) fire potential, (7) basal area, (8) Wildlife Habitat Relation (WHR) size class, and (9) late successional rank.

Target levels of the modeling goals are established for each strategy. Measurement of the attainment of a specific structure goal is determined within discrete intervals defined by the goal width. Basically, the goal width allows flexibility in meeting the goal target. For example, the large trees per acre has a neighborhood (width) of one tree per acre (table 2). Thus if the target is four large trees, 4.15 trees equally attain the target as 4.75 trees. The application of neighborhoods always occurs above the target, thus, the target is a "floor."

A simulation run, in other words prescription, is developed by first specifying the desired magnitude (target) of each of the above goals for the target strata, for example, 12 tpa >30 inches d.b.h. and an LSOG rank of 4. Two additional data are input along with the target; relative importance of each goal (in other words a weight) and a numeric penalty (a multiplier) for not meeting the target. Examples of goal targets, metric weights, and penalties used in the policy analysis are shown in table 3.

Solving for the Harvest Intensity in a Period

One of the five activities discussed above is partial harvesting. The harvesting activity allows for the option of removing trees, by species group and diameter class, when so doing moves the stand's future structure towards a structure that more closely resembles the desired management goal.

FVSPGM determines the periodic harvest intensity, in other words which trees to cut by species and d.b.h. class, by evaluating a large number of potential solutions. These potential solutions are evaluated in two steps. The first step

Table 2—Goal/metric widths and descriptions for use in stand optimization routines.

Goal/metric #	Goal/metric width	Goal/metric description
1.	1 tree	Large trees per acre
2.	5 percent	Total canopy closure
3.	5 percent	Intermediate canopy
4.	1 snag	Snags per acre
5.	1 chunk	Down wood per acre
6.	5 units	Fire potential index
7.	5 sq. ft.	Basal area per acre
8.	n/a	WHR size class
9.	n/a	LSOG rank

Table 3—Example of target levels, weights, and penalties by goal and aspect.

Matrix rank 3 All aspects		Look Ahead = 20 years		
Metric	Target	Weight	Penalty	Achieve
Lg_Trees	6	8	2	Exactly
Canopy	50 percent	4	1	Exactly
I_Canopy	n/a	n/a	n/a	n/a
Snags	2	1	1	At least
Down_Wood	n/a	n/a	n/a	n/a
Fire_Hazard	10	7	2	At most
Insects	n/a	n/a	n/a	n/a
WHR_Size	n/a	n/a	n/a	n/a
LSOG_Rank	3	5	3	Exactly

ALSE rank 4 Southwest		Look Ahead = 30 years		
Metric	Target	Weight	Penalty	Achieve
Lg_Trees	12	8	2	At least
Canopy	50 percent	4	1	Exactly
I_Canopy	20 percent	1	1	At least
Snags	4	1	1	At least
Down_Wood	n/a	n/a	n/a	n/a
Fire_Hazard	15	1	2	At most
Insects	n/a	n/a	n/a	n/a
WHR_Size	n/a	n/a	n/a	n/a
LSOG_Rank	5	5	3	At least

determines a family of solutions that equally minimize the difference between the structure resulting from the solution and the target stand structure through time (based on the goal class width). The second step evaluates this family of solutions to identify the solution that has the highest economic value, in other words highest present net value of the stand through time including the ending inventory.

For example, FVSGM may generate over 600 different harvest intensities for a single period. These intensities vary by the number of stems removed and the species and size classes of the removals. Within these 600 intensities, possibly 20 or more may equally meet the stand structure targets; in other words one solution may have less large trees than another, but compensates with a higher canopy density. For each of the 20 or more harvest intensities that meet the targets, the economic value is calculated and the intensity with the highest present net value is selected. In the case that all candidate intensities are negative, the candidate with the lowest negative value is chosen. It is important to note that although the intensity with the highest present net value is being chosen, the present net value criteria is being used as a way of finding the most efficient way to reach a management goal given that more than one way exists to reach the structural targets representing the goal.

Constraints on the Search for the Best Harvest Intensity

The harvest search procedure, and thus the solutions, are constrained by two parameters: (1) a minimum net board foot harvest that varies by slope (2,800 bf on slopes less than

40 percent, 5,000 bf on slopes greater than 40 percent), and (2) a minimum residual basal area of 75 square feet per acre. These limits help insure that the harvests will pay for themselves and that the analysis will not select "nonsense" solutions, such as very low harvests and very low basal areas, that are outside the capability of the simulation to accurately represent. The only exception to minimum levels of harvest involve the biomass harvest activity. If ladder fuels exist under canopy conditions that could result in crown fire, the ladder fuels are removed regardless of the minimum volume target during the first two periods of an ALSE management goal strategy that permits harvest or in the minimize fire hazard management goal even if the revenues will be negative.

Modeling Fire at the Stand Level

Defining Fire Hazard

A fire hazard index was developed to help guide the growth simulations toward structures that would reduce the likelihood of stand terminating fires, a goal of the stratum level simulations. The index incorporates both pre-fire fire conditions and post-fire effects, and is calculated based on three factors:

1. Percent of basal area a fire would kill if a fire occurred post-treatment.
2. Difference between the pre-treatment flame length and post-treatment flame length.
3. Post-treatment percent canopy closure.

The percent basal area killed is based on the predicted flame length. The predicted flame length is used to derive the scorch height. The probability of a tree of a given species and diameter dying due to fire can then be estimated as a function of the scorch height. The flame length is based on the current forest structure condition aggregated by vegetation type and the silvicultural activities through time. Flame length is assumed to vary with fuel loading, aspect, and slope. For each administrative unit, flame lengths for the existing stand were established for each vegetation strata, slope, and aspect. Using rules developed by Bahro (1996), flame lengths changed over time depending upon management actions, stand development, slope, and aspect.

Fire Mortality at the Stand Level

FVSPGM takes into account two kinds of fire: wildfire, and prescribed fire. Wildfire is assumed to occur under a specific set of extreme weather conditions that are established for each administrative area by the SNEP fire disturbance group. Prescribed fire is assumed to occur under less severe weather conditions.

FVSPGM estimates stem mortality due to wildfire given the flame length, species, diameter, height to the live crown, canopy closure, and topography. The initial flame lengths are input into FVSPGM by forest type, slope, and aspect. The flame length increases if no activity occurs in a stand, and decreases as a function of type of activity (prescribed burning, fuel break installation/maintenance, or thinning

and partial harvest). A harvest that cuts trees for which 80 percent or more of the harvested basal area comes from trees less than 11 inches d.b.h. is defined as a precommercial thinning and has a different flame length response than a selective harvest of larger trees.

Stem mortality is calculated based on a table of fire effects probabilities for noncrown fires derived by Bahro (1995) using the USDA First Order Fire Effects Model (Reinhardt and others 1997). These probabilities are by 2 inch d.b.h. classes for 3 species groups (other conifer, red fir, cedar, hardwoods; sugar and ponderosa pine; Douglas-fir), and are referenced by scorch height. FVSPGM sums the fire effects probabilities for all d.b.h./species groups in the stand. The summed probabilities are then multiplied by the standing basal area in each d.b.h./species group to determine the percent of basal area killed in the stand. These probabilities are also multiplied by standing trees per acre to determine trees per acre killed by the fire.

Stand replacement fires are modeled as killing all stems in the stand, in other words stand terminating. These fires are modeled to occur when the flame length is greater than 6 feet and the canopy closure is greater than 70 percent; or when there is a presence of ladder fuels (d.b.h. < 8 inches) and the flame length is long enough to get into these crowns (and canopy closure is greater than 70 percent). Ladder fuels are present and susceptible to carrying fire when the average height to the live crown base of these stems is less than 4.5 times the flame length, less 7.5 feet.

The level of salvage is a function of the strategy. Strategies for the matrix lands, such as Matrix-Rank 3, or Max NPV allow salvage of 66 percent of the volume, except for the three largest snags created by the fire. The ALSE goal sets leave all burned stems greater than 24 inches as snags and salvage 66 percent of the stems 12 to 24 inches d.b.h.

Prescribed burning is modeled by removing trees from the stand based on predefined mortality probabilities, supplied by the SNEP fire disturbance group. Stems greater in size than the minimum snag diameter, 24 inches, are recruited into the stand snag list. No volume is salvaged from prescribed burns.

Defensible Fuel Profile Zones (Fuel Breaks)

The objective of the "fuel break" activity is to establish forest conditions under which it is likely that suppression forces could stop the spread of a wildfire. These forest conditions are expressed as a combination of flame length, which affects the resistance to control at the ground level, and canopy closure that reflects the opportunity for fire to spread through the crowns.

The establishment of a fuel break is modeled as a harvest, which brings the residual canopy closure down to 30 percent. This canopy reduction is reached through a two-step harvesting process that removes small to large trees. The first step brings the canopy down to 40 percent, the second step brings the canopy to 30 percent. If a fuel break installation activity has been specified, the fuel break algorithm will begin if the stand currently has more than 40 percent canopy closure. If the stand does not have more than 40 percent canopy closure, no activity is undertaken. The fuel breaks must be installed in either the first or second period. They are maintained, in other words the canopy is reduced to below 30 percent, every 20 years. Observations of growth indicate the canopy typically reaches about 50 percent closure approximately 20 years after it has been thinned back to 30 percent crown closure.

Examples of FVSPGM Output

An example of the FVSPGM yield streams for five different strategies has been constructed for the vegetation strata M3G (mixed conifer, size class three, heavy canopy closure) on site one, southwest aspect, ground slope less than 40 percent. The five strategy examples are: 1. ALSE - Rank 4; 2. Matrix - Rank 3; 3. Matrix - Rank 2; 4. Maximize Present Net Value; 5. Minimize Fire Hazard.

In this example analysis for those prescriptions that permit harvesting, we used the prescription "HHHHH," which potentially permits a harvest each period. Whether a harvest actually takes place each period will depend upon the contribution of a potential harvest to the goal. We also illustrate two other prescriptions that might be used to reach goals when harvest is not allowed: (1) "NNNNN" (no action) and (2) "PPPPP" (prescribed burn each decade) to show effects where harvest is not allowed. A third prescription, Fuel Break, illustrates establishing a defensible fuel profile zone.

The first time period begins in 1996 so the midpoint is the year 2001. The number of harvest entries, level of harvest removals, effect on LSOG rank, mean stand diameter, canopy closure, fire hazard, and residual stand value are compared (table 4). Activities are permitted for the first five 10 year periods, but we have shown the simulation for ten 10 year periods to illustrate the longer run effects.

Examining the first five rows of table 4, one can see the prescriptions harvest intensity increase as the LSOG strategy for the strata is relaxed, for example, 50 year harvest levels start at 20 mbf for LSOG rank 4, and increases approximately 10 mbf for each decrease in rank, to 53 mbf when no rank goal is specified. The present net value follows the same pattern, with the maximize PNV strategy having the highest PNV. The large trees component, as expected, is also strongly correlated with the LSOG strategy, with higher LSOG simulated strategies having more per acre.

The fire hazard index shows some of the least variability, with the Fuel Break strategy having the single lowest value. Next is a cluster of five prescriptions with an average score of approximately 12, representing a step up in fires risk. This clustering is due to all of these strategies having explicit goals to minimize the fire hazard. The maximize PNV strategy has the highest hazard score without being a crown fire, and is the only prescription that did not have any fire related goals. The No Action simulation results in a forest structure which, if exposed to fire, will result in a stand terminating crown fire.

A last observation is the close year 50 volumes of the Matrix Rank 2, Maximize PNV, and Fuel Break strategies, 32.1, 32.8, and 34.6 mbf/acre, respectively. However, the similarities stop with volume, the basal area for the Maximize PNV is 219, but only 146 and 137 for Matrix Rank 2 and Fuel Break. These last two prescriptions with less than 150

Table 4—Summary comparison of simulation results under different goals.

Goal	Ending rank Beg. = 3	Ending trees >30 in. TPA Beg. = 9.6	Ending trees >40 in. TPA Beg. = 2.0	Ending canopy closure percent Beg. = 87	Ending mean diameter[a] inches Beg. = 12.7	Ending basal area Beg. = 244	Ending inventory MBF Beg. = 35.7	Ending WHR Beg. = M4M	Harvest volume MBF	Present net value	End fire hazard index Beg. = 99	Number of harvest entries[b]
1. No Action	4	23.2	9.2	129	16.0	358	68.0	M6D	0.0	$409	99	0
2. ALSE Rank 4	4	21.7	8.9	56	20.7	252	59.2	M4M	20.0	$1,878	13	4
3. Matrix Rank 3	4	15.7	6.8	49	18.7	189	47.8	P4M	30.0	$3,980	10	4
4. Matrix Rank 2	2	13.6	5.5	37	19.7	146	32.1	M4P	39.8	$5,660	11	4
5. Maximize PNV	3	6.3	0.8	68	13.4	219	32.8	M6M	53.1	$7,401	17	5
6. Min. Fire Hazard	4	14.6	6.7	45	22.8	212	42.7	M5M	30.4	$4,148	13	4
7. Prescribed Fire	4	20.3	8.4	63	24.7	262	55.6	M5M	0	$199	14	0
8. Fuel Break	3	11.8	6.8	30	28.4	137	34.6	M5P	21.1	$3,767	7	5

NOTE: Except PNV, all ending outputs are for the end of the fifth period. PNV is calculated using outputs of the first five periods plus residual inventory value projected at the tenth period.

[a]Mean diameter is Quadratic Mean Diameter (QMD).
[b]Harvest entries are over the first five periods.

TPA = trees/acre
MBF = thousand board feet
WHR = Wildlife Habitat Rating

square feet diverge in their treatment of the smaller merchantable stems, with the Fuel Break strategy aggressively removing these stems. This is illustrated in the quadratic mean diameter, Matrix Rank 2 yields a quadratic mean diameter (qmd) of 19.7 inches, whereas the Fuel Break strategy has a qmd of 28.4 inches in year 50.

Output for Policy Simulation

A file of abbreviated information from the FVSPGM prescriptions containing the harvest per period, rank, WHR, flame length, hazard index, and basal area that would be killed if a fire occurred under extreme weather conditions is prepared for export to the policy analysis model. A prescription is produced for each combination of strategy, stratum, activity, slope, and aspect. The prescriptions for a typical National Forest run include prescriptions for each of 6 strategies x 50 vegetation strata x 324 activities x 2 slopes x 2 aspects or approximately 390,000 prescriptions. These prescriptions then become the pool of activities from which the policy simulation model can draw from to achieve the objectives for each administrative unit (National Forest or National Park). A separate pool of prescriptions is prepared for each administrative unit.

Conclusions

The combination of the sheer volume of yields that needed to be generated for the Sierra Nevada Ecosystem Project, and the number of people involved in their creation, required the development of a goal based growth and yield modeling tool. The goal based system FVSPGM allowed SNEP team members to focus on and specify where they wanted strata to go structurally for a given management strategy, without having to specify the details of harvest intensities, in other words thin from below, thin from above, and so forth.

FVSPGM's goal structure distinguishes it from other single stand optimization algorithms such as DPDFSIM

(Johnson and Sleavy 1984). The goals are tied together through the use of the ecological objective function. This function guides FVSPGM to achieve forest structures as close to the goals as possible by minimizing the deviation between the stand's current state and the input silvicultural and ecological goals.

The goal format proved to be especially valuable when the prescriptions needed to respond to the possibility of wildfire occurring during the planning horizon. This possibility could be considered a meta-state so that for each strategy, a prescription is developed for the possibility that a wildfire occurs one or more times during the planning horizon. These "best" paths (prescriptions) given a fire occurs are then passed to the policy simulator which simulates the stochastic occurrence of wildfire and management's reaction to it. Although our examples of FVSPGM did not illustrate the occurrence of fire in the "NNNNN" and "HHHHH" goal sets due to manuscript space limitations, the additional yield streams with fire provide management with not only an estimate of the fire effects that would occur, but also what management actions could be taken to maintain progress to the original goal given that the fire does occur.

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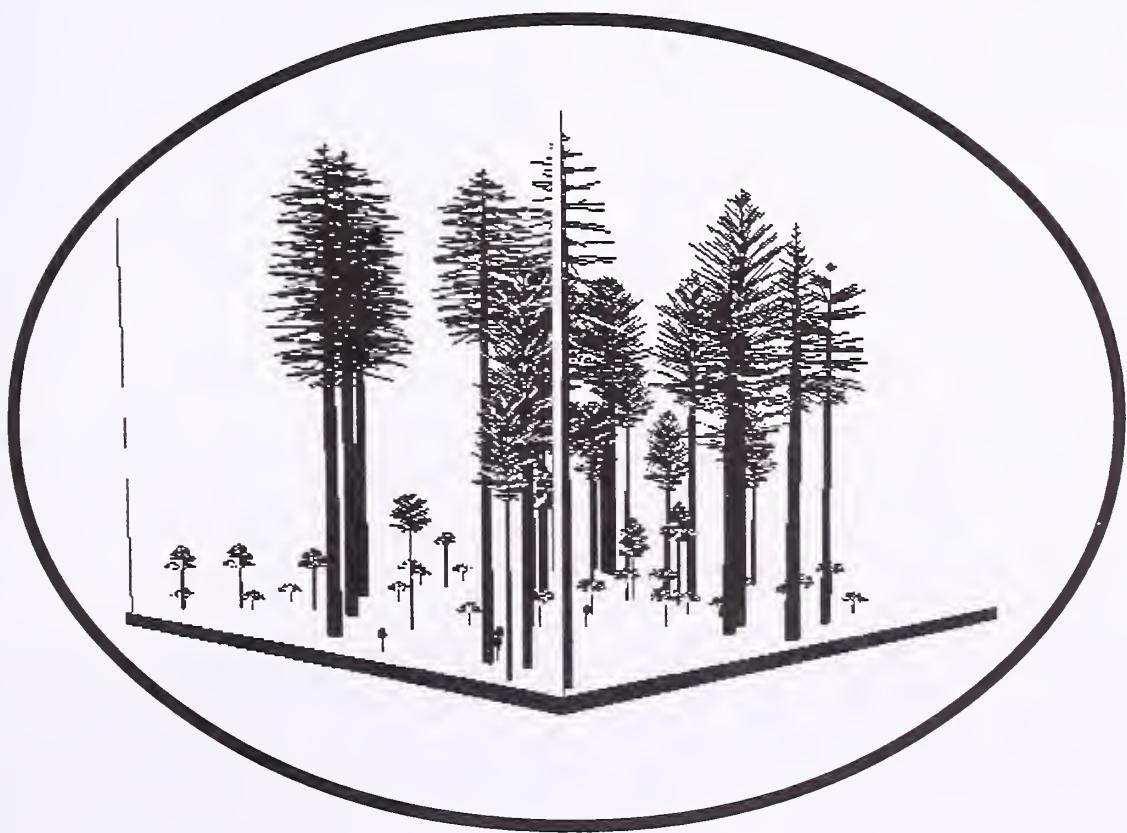
A Multistand Assessment Approach for Evaluating Insects and Diseases, Establishing Treatment Priorities, and Predicting Vegetative Development

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Abstract—Insect and disease impacts must be included when assessing vegetative conditions now and in the future. Insect and disease model extensions to FVS are available to aid in assessing vegetative development. A method for describing initial conditions for dwarf mistletoes and root diseases that can be used to provide input to the Western Root Disease Model and the Interim Dwarf Mistletoe Model is described. This method can be used in extensive reconnaissance. Results of extensive surveys from a portion of a 6,000 acre planning area are presented. Root diseases are estimated to occur at some level in 90 percent of the stands. WRDM keyword development strategy based on root disease severity is presented. Intensive examinations and use of preexisting data will be used to build FVS treelist files. Modeled stands will then be used to establish treatment priorities.

Root diseases, bark beetles, and dwarf mistletoes are frequently encountered disturbance agents in the mixed conifer forests of the southern Oregon Cascades. They cause growth loss, mortality, and dieback of individual trees and can create openings, increase vegetative diversity, change stand structure and composition, and influence vegetative succession in both directions, at either the stand or landscape level. These organisms may be indicators of tree stress; stressors can include overstocking, moisture deficiency, nutrient imbalances, soil compaction, or the presence of other insects or diseases. They may be associated with a particular site, maintaining inoculum levels in a relatively limited area for decades. Knowing their incidence and current level of impact and understanding how insect and pathogen impacts vary by site and are influenced by management activities are important considerations for predicting what the vegetative resource for a given area is likely to be in the future.

Insect and Disease Models

The recent development of several insect and disease model extensions to FVS, as well as the refinement of the already existing dwarf mistletoe model within the FVS structure, have given us valuable tools for incorporating insect and disease impacts into vegetative resource planning. Particularly important for modeling stands in the mixed conifer forest of the southern Cascades are the Interim Dwarf Mistletoe Model (IDMM) (Hawksworth and others 1993) and the Western Root Disease Model version 3.0 (WRDM) (Beukema and Kurz 1996).

The IDMM models growth impacts, mortality, spread, and intensification of several species of dwarf mistletoes (*Arceuthobium* spp.) commonly found in the Western United States and Canada. It relies on the user supplying individual tree dwarf mistletoe severity ratings based on the Hawksworth six-class rating system (Hawksworth 1977). The model operates in FVS whenever dwarf mistletoe codes are included in the FVS treelist file. Its keywords can be used to extract dwarf mistletoe-specific data tables, to specify dwarf-mistletoe management in conjunction with FVS harvest keywords, or to modify IDMM assumptions to calibrate the model to local conditions.

The WRDM models growth impacts, mortality, spread within root disease centers, and spread into the healthy portion of a stand for Armillaria root disease (caused by *Armillaria ostoyae*), laminated root rot (caused by *Phellinus weirii*), or both the S and P types of annosus root disease (caused by *Heterobasidion annosum*). It also models root disease interaction with bark beetles or can depict density-dependent or windthrow-related bark beetle activity that is not associated with the root disease in a stand. Keywords are available to extract detailed root disease information or model root disease management activities such as pulling stumps or applying borate. Several keywords can be used to modify model assumptions.

Different WRDM keywords or keyword combinations can be used to initialize current root disease conditions in a stand depending on whether there were data collected at the tree-level, plot-level, stand-level, or in some combination. Regardless, the WRDM must be supplied with at least a minimal description of the area affected, the proportion of trees affected, and how the root disease is distributed. With the exception of being able to model both the S and P types of annosus root disease in the same stand, the WRDM can only model one root disease at a time.

Because the WRDM was developed as a westwide model covering the Western United States and Canada, its defaults may not appropriately describe root disease behavior for all conditions; species susceptibility, spread rates, and other factors can vary greatly from Region to Region and site to site. This broad scope makes it a very flexible model but also makes it important that the user is comfortable with the model's behavior and therefore its assumptions regarding

species susceptibility, infection probabilities, and spread. Local calibration may be important.

Regardless of their sophistication or power, the insect and disease models will only be useful when they are provided with realistic input data. In the Pacific Northwest, we are only now acquiring the kinds of insect and disease information required by these models for Forest or Regional-level assessments. Many of the stand-level datasets available for Federal lands do not have an adequate description of insects and diseases; this is particularly true for root diseases. Funding for detailed, plot-based stand examinations that could be used to acquire this information is decreasing. Many assessments rely on "walk-through" types of reconnaissance for evaluating vegetative conditions. The challenge before us, therefore, is to develop an efficient method for collecting and describing insect and disease impacts that can be used in vegetative modeling.

North 140 Project

Analysis of the North 140 Planning Area, located on the southern end of the Butte Falls Ranger District, Rogue River National Forest in Oregon, provided an opportunity to approach characterization and modeling of multiple stands where diseases are major concerns, but little information is available on their incidence and impact. The planning area encompasses approximately 6,000 acres (2,428 ha) of mixed conifer forests ranging in elevation from 3,800 to 5,400 feet (1,160 to 1,646 m). Dominant tree species include Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), Shasta red fir (*A. magnifica* var. *shastensis*), and ponderosa pine (*Pinus ponderosa*). Other species present include sugar pine (*P. lambertiana*), western white pine (*P. monticola*), lodgepole pine (*P. contorta*), Pacific yew (*Taxus brevifolia*), incense cedar (*Calocedrus decurrens*), golden chinquapin (*Castanopsis chrysophylla*), bigleaf maple (*Acer macrophyllum*), Oregon white oak (*Quercus garryana*), California back oak (*Q. kelloggii*), and Pacific dogwood (*Cornus nutallii*). Much of the area has been harvested. Previous treatments include regeneration harvest and single tree selection. High incidence of Douglas-fir dwarf mistletoe (*A. douglasii*) was recognized; many seed-tree and shelterwood harvest units as well as many partially entered stands have dwarf mistletoe-infected overstory trees. Few data were available describing severity of the dwarf mistletoe or identifying those stands where potential future impact of dwarf mistletoe would be high based on stand composition and structure. Root diseases had been considered a minor influence in these stands until recent reconnaissance indicated that not only was root disease incidence higher than previously thought, but that several different root diseases were present and causing extensive mortality.

Developing Survey Protocol

The initial phase of the analysis involved developing a protocol for describing the current vegetative component of each stand in the planning area, including incidence and impacts of major diseases and insects. This description needed to include basic information about the vegetative component so that stands could be grouped by simple descriptors such as species composition, structure, age, and size classes. We needed to have enough information to characterize dwarf mistletoes and root diseases according to input requirements of the IDMM and the WRDM. We also wanted to build GIS layers describing root disease severity and dwarf mistletoe incidence and impact. Information needed to be sufficient to prioritize stands for treatments. The data collection had to be associated with walk-through reconnaissance rather than plot-based examination. Some level of experience and comfort by the data collectors for this approach to reconnaissance was assumed in the survey design; data collectors for the North 140 project were all experienced silviculturists and prescription writers. Coverage was expected to be, on average, 75 acres (30 ha) per day.

Descriptors of vegetation for each stand included: (1) canopy closure total, (2) number of canopy layers, (3) canopy closure by layer, (4) size class, average diameter, and breast height age estimated for each canopy layer, (5) estimated percentage of the four principal species in each canopy layer, (6) estimated percent mortality for each species in each canopy layer, (7) estimated percent of dwarf mistletoe-infected trees for each species in each canopy layer, (8) estimated percent of each dwarf-mistletoe infected species in each canopy layer by dwarf mistletoe severity ratings of low (Hawksworth rating 1 and 2), moderate (Hawksworth rating 3 and 4), and high (Hawksworth rating 5 and 6), (9) plant association, (10) root disease severity rating, (11) root disease(s) present and tree species affected, (12) estimate of the percent of stumps infected by categories: less than 1 percent, 1 to 5 percent, 5 to 10 percent, greater than 10 percent, (13) percent of each tree species infested by bark beetles with an estimate of the proportion recently killed and those that are older dead, and (14) any other insects or pathogens noted, particularly the presence of white pine blister rust.

The Root Disease Severity Rating scale (RDSR) (table 1) was based on a scale developed for stands in Montana and North Idaho by plant pathologist Susan Hagle (Hagle 1985). The Hagle system estimates root disease impact based on canopy loss due to root disease. The scale used in the North 140 project redefines canopy loss groupings and further describes how root disease is distributed in the stand.

Table 1—Root Disease Severity Ratings for the North 140 Planning Area analysis.

Root disease severity rating		Canopy reduction
Rating	**Description**	
		Percent
0	No root disease found	
1	Stump infection only	
2	Minor root disease	<1
3	Scattered infection	1 to 10
4	Distinct pockets	1 to 10
5	Scattered infection	11 to 30
6	Distinct pockets	11 to 30
7	Scattered infection	30 to 50
8	Distinct pockets	30 to 50
9	Any distribution	>50

The Root Disease Severity Rating scale and other root disease information provides the basic framework for describing WRDM root disease initial conditions using the RRINIT keyword. In RRINIT the user specifies how the root disease is distributed. When a stand is described as having scattered infection, the entire stand is modeled as one root disease center and the proportion of trees that are infected is based on the proportion of canopy loss, if the stand is composed predominantly of susceptible species. Within the framework of the WRDM, when root disease is not scattered, but occurs in distinct pockets, the proportion of the area affected is much more important than the actual number of infected trees. Therefore, when a RDSR is used that describes distinct pockets, the proportion of canopy loss is multiplied by the total number of acres in the stand to estimate the number of acres in the stand that are in root disease. The root disease being modeled (Armillaria root disease, laminated root rot, and so forth) is also designated within the RRINIT structure. All stands within the planning area are scheduled for extensive survey; thus all stands within the planning area that have root diseases modeled by the WRDM will have WRDM keywords built from the data if those root diseases occur in the stand.

Preliminary Results

Approximately half of the North 140 Planning Area has been surveyed at the time of this writing. Only root disease information has been evaluated thus far.

Ninety percent of the stands visited had root disease present. Sixty-four percent of the stands had current root disease impacts that can be considered minor; 10 percent or less of the canopy had been affected. Twenty percent of the stands had RDSRs of five or six, where 11 to 30 percent of the canopy is lost due to root disease. Five percent of the stands have an RDSR of seven with 31 to 50 percent canopy loss and 1 percent of the stands has greater than 50 percent canopy openings due to root disease.

Armillaria root disease was found with the greatest frequency; it occurred in 68 percent of the stands, followed by annosus root disease (found in 64 percent of the stands), laminated root rot (found in 27 percent of the stands), and black stain root disease, caused by *Leptographium wageneri*, which occurred in 12 percent of the stands. Root diseases occurred together in the same stand; 5 percent of the stands had all four root diseases present. The most common combination found was that of Armillaria root disease with annosus root disease, which occurred in 41 percent of the stands.

The preponderance of stands with more than one root disease presented a challenge for describing root disease conditions for the WRDM. Since the WRDM can model only one root disease at a time, it became necessary to use additional keywords that modify model behavior to simulate root disease combinations. Three keywords were used to accomplish this: TTDMULT, which modifies the time required for tree death, INFMULT, which changes infection probability, and INFKILL, which controls the proportion of the root system that must be colonized for tree death to occur. In all combination cases, multipliers were increased to some degree for white fir.

Black stain root disease is not modeled by the current WRDM system and was ignored in this first phase of analysis.

Multiple-pest modeling is also a consideration for the area because dwarf mistletoes, root diseases, and bark beetles are frequently found together in the same stand. Modeled separately, these insect and disease models are independent of one another and the potential exists for double counting mortality. The WRDM, however, includes built-in bark beetle functions that are designed to work with and without root disease; therefore, any double counting of mortality is taken care of internally and the multiple pest interaction should be realistic. The IDMM and the WRDM working together may cause an increase in expected mortality if the same hosts are affected and if the impacts are high for that host. Survey results so far indicate that dwarf mistletoe has been found predominantly on Douglas-fir with some infection in white fir. White fir dwarf mistletoe impacts are generally low, even when a tree is severely infected. Douglas-fir dwarf mistletoe does not appear to be at high levels in those same stands where Douglas-fir is greatly affected by root disease, such as in the stands with laminated root rot. Thus far, dwarf mistletoe-root disease interaction is not an issue for the North 140 analysis.

Intensive Surveying

Forest Vegetation Simulator treelist files will be necessary to begin growing the North 140 stands into the future. Previously completed formal stand examinations are available for some stands within the Planning Area and will be used to build treelists for those stands and others that are considered similar based on their recent description. Intensive surveying of a selection of stands is planned to build treelists for those stands that are significantly different. The choice of which categories of stands will be intensively surveyed will be based on the range of RDSRs, dwarf mistletoe infection levels, and unique age-vegetation combinations that occur. These intensive examinations will also be used to verify assumptions made regarding WRDM keywords based on RDSRs.

When both the extensive and intensive surveys are completed, the stands will be modeled into the future using FVS. After the modeling phase is completed, priorities for immediate treatment will be based on resource objectives, stand and site conditions that currently occur, projected vegetative development, and the arrangement and relationship of stands in time and space across the planning area.

Many other uses are planned for the information gathered in this project. Relationships between site and stand characteristics and insect and disease incidence and impact will be analyzed for patterns that may be useful for developing predictive models or risk/hazard rating systems for mixed conifer stands in the southern Cascades. The GIS layer developed as a result of this project will hopefully serve as a model for other insect and disease-related GIS efforts. Among many other possibilities, these data may also be useful for successional modeling efforts that Forest personnel are interested in pursuing.

The North 140 Planning Area analysis indicates that it is possible to describe, in quantitative terms, insect and disease impacts using a relatively efficient data-gathering procedure. These descriptors can then be used in spatial analysis and to model the agents and their impacts.

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Successional Simulations Using the Forest Vegetation Simulator and Multi-Pest Scenarios for Various Levels of Planning

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Abstract—Successional pathways can be modeled using the Forest Vegetation Simulator (FVS). Formal pest extensions and simple mortality functions can be linked to FVS in order to simulate impacts associated with epidemics of selected disturbance agents. The logic and keyword sets used to include multi-pest impacts in FVS simulations are described. This procedure is currently being used by the southwestern Idaho Ecogroup for planning purposes.

Change in vegetation or succession proceeds toward predictable climax plant communities, and these successional pathways can be modeled using simulation models such as the Forest Vegetation Simulator (FVS) (Wykoff and others 1982). An important component of this simulation model is the ability to model disturbances that may redirect, slow down, or speed up succession. Insects and diseases have long been regarded as important biotic disturbances agents that kill trees, slow growth, or cause other changes, and the result is a change in the vegetation. Therefore, there is a need to include impacts caused by these disturbance agents in successional simulations.

During the last 6 years, we have been working at various planning levels developing multi-pest scenarios for use in FVS. In 1991, we began working with personnel from timber management, Targhee National Forest, on a procedure to incorporate pest impacts into yield tables for the Forest Plan Revision. Together we decided to utilize the Teton Variant (6.0) of Prognosis, the predecessor of FVS, and three existing pest extensions: Western Spruce Budworm Damage Model (Crookston and others 1990), Douglas-fir Beetle Impact Model (Marsden and others 1994), and Mountain Pine Beetle Model (Gladden and others 1990). Previously, each pest extension was linked independently to the Prognosis model, but for this effort we obtained a version linking all three pest extensions to facilitate our multi-pest scenario.

To include pest extensions in a biologically meaningful manner, we had to consider the following questions for each pest species.

What are the stand attributes that predispose the site to an outbreak? If we identify these attributes we can call pest extensions when attributes indicate susceptibility.

Hazard rating schemes were developed for each pest species using the appropriate predisposing attributes. Mountain pine beetle and Douglas-fir beetle pest extensions were only called or triggered in the FVS run when hazard rating criteria equaled or exceeded hazard threshold values.

What is the duration of an outbreak? Duration is defined for our analysis as the number of years an outbreak might last within a cycle. Mountain pine beetle and Douglas-fir beetle pest extensions control the duration of outbreaks. The western spruce budworm damage model allows the user to set the duration. We chose to use the western spruce budworm hazard rating to set the duration of an outbreak (for example, high hazard stands had 15 year outbreaks while low hazard stands had 5 year outbreaks).

What is the intensity of an outbreak? Western spruce budworm defoliates host trees, and the intensity of defoliation is estimated as the percent of new foliage defoliated each year of the outbreak. Intensity of defoliation is input into the western spruce budworm damage model. We chose to use our hazard rating scheme to select the appropriate level of defoliation (for example, high hazard stands had higher levels of defoliation than moderate or low hazard stands). Bark beetles kill trees, and mortality is estimated as the number of dead trees per acre per year by diameter class of host species or as a percentage of host trees within a defined diameter range. Mountain pine beetle and Douglas-fir beetle pest extensions control the level of mortality based upon stand conditions. However, the user can modify the default mortality level.

How frequently should there be an outbreak? Frequency indicates how may outbreaks might occur over the planning horizon and the interval between outbreaks. Initially we allowed bark beetle outbreaks to begin every 20 years as long as the stand remained susceptible. Similarly, budworm outbreaks occurred in alternating cycles from bark beetle outbreaks. This outbreak schedule eliminated possible problems associated with two or more pests affecting the same host tree species. The western spruce budworm pest extension was called in the odd cycles while the Douglas-fir beetle and mountain pine beetle pest extensions were only called in even cycles when hazard ratings indicated susceptible stand conditions.

At this point, we selected inventory datafiles for 14 mature Douglas-fir stands to assess the behavior of our multi-pest modeling effort. A Prognosis run for each of the 14 stands without pest extensions was completed and outputs from all 14 runs were averaged using the post processor. The average output became our baseline for comparison among runs. We

incrementally added the western spruce budworm pest extension, the Douglas-fir beetle pest extension, and the mountain pine beetle pest extension and graphically compared the outputs, most specifically cubic foot volume over time, to the baseline run. We worked closely with the silviculturist to determine if the output looked logical. Modifications to the pest extensions were made to more closely approximate what occurs within a stand and on an average across a landscape.

Our multi-pest scenario has evolved, based upon technical assistance requests from National Forests within the area covered by the Central Idaho Variant of FVS, to include existing pest extensions and simple mortality functions to simulate effects of other pests (western pine beetle, fir engraver beetle, and spruce beetle).

One of our most recent accomplishments has been a prototype simulation of a successional pathway with management and a successional pathway without management for a stand representing a grand fir/mountain maple (ABGR/ACGL) habitat type on the Payette National Forest (Weatherby and others 1997). The simulation uses the Central Idaho Variant of FVS and several pest extensions. Stand exam data for a 90 year old stand are used to initiate the simulation depicting changes in stand structure and composition from 1994 to 2094. Site specific stand conditions trigger pest outbreaks. Impacts associated with Douglas-fir beetle and western spruce budworm are simulated using existing pest extension models, and impacts associated with western pine beetle and fir engraver beetle outbreaks are simulated using FIXMORT keywords. The Mistletoe Model (Hawksworth and others 1992) inherent in FVS is called if mistletoe infection was recorded in the input tree data. The Stand Visualization System (SVS) (McGaughey and McCarter 1995) produces diagrams of the stand based upon the decadal treelists generated by FVS. Effects of wildfire are predicted using a probability of mortality equation developed by Reinhardt and Ryan (1988). Effects of a wildfire occurring at the beginning of the simulation, after 50 years of simulation, or at the end of the simulation are depicted through manipulations of the SVS program.

This multi-pest scenario has been tentatively adopted by the Southwest Idaho Ecogroup Team (Boise, Payette, and Sawtooth National Forests) charged with developing volume tables for Forest Plan Revisions. Modifications to the initial multi-pest scenario continue to be made including the introduction of random triggers to initiate western pine beetle, fir engraver beetle and spruce beetle outbreaks and the inclusion of keywords to represent effects of endemic and epidemic beetle caused mortality.

Presently, our multi-pest scenario schedules budworm outbreaks to occur in cycles 1, 5, and 9 if host tree species are found in the stand. Forty years transpire between the beginning of each budworm outbreak. The duration and the intensity of defoliation are determined by the hazard rating utilizing site specific data. Bark beetle impacts can occur in any cycle except for the first cycle. Outbreaks are possible when hazard rating criteria are met. Stochastic outbreak triggers initiate bark beetle outbreaks.

The following examples illustrate our hazard rating schemes and methods for triggering the Douglas-fir beetle pest extension, the western spruce budworm pest extension, and a simple mortality function to simulate a western pine

beetle outbreak. A complete listing of the keyword file for the multi-pest scenario is available in digital form from the authors.

Simulating Impacts from Douglas-fir Beetle

Using the Compute component of the Event Monitor (Crookston 1990), we calculated or extracted the following variables. These variables are computed each cycle.

```
COMPUTE        0
REMD = FRAC(CYCLE/2)
TO_BA = SPMCDBH(2,0,0)
DF_BA = SPMCDBH(2,3,0,9)
PERBADF = DF_BA / TO_BA
END
```

Since we allowed bark beetle outbreaks to occur in even cycles, we compute a value stored in REMD using a function called FRAC(CYCLE/2). This takes the cycle number and divides it by 2. The remainder or fractional part is stored in REMD. If the value in REMD is equal to zero, we conclude the cycle is even. If the value is greater than zero, we conclude the cycle is odd. We compute the basal area of all trees in the stand (TO_BA) using the SPMCDBH function from the event monitor as an indication of tree density. Next we compute the basal area of Douglas-fir trees greater than 9 inches (DF_BA) to indicate the amount of host. Then we compute the percent of host (PERBADF) by dividing the amount of host (DF_BA) by the total basal area of the stand (TO_BA). These variables flag even or odd cycles, and are used to hazard rate the susceptibility of the stand to a Douglas-fir beetle outbreak.

The next example uses the IF/THEN component of the Event Monitor. We use this component to trigger an outbreak if the hazard rating conditions are satisfied.

```
IF             0
TO_BA GT 120 AND PERBADF GT .25 AND REMD EQ 0
THEN
DFB
MANSCHED
RANSTART
END
ENDIF
```

At the beginning of each cycle, FVS will evaluate the conditions of the IF statement. IF the total basal area of the stand is greater than 120 and the proportion of host is greater than 0.25 and the cycle is even, THEN call the Douglas-fir beetle model, manually schedule a regional outbreak, and randomly start a local outbreak. The END closes the pest model and the ENDIF closes the IF/THEN component.

Once called, the Douglas-fir Beetle model will determine the duration of the outbreak (usually 4 years) and the intensity of the outbreak (trees per acre killed by diameter class per year). Since we used RANSTART, the model will test the probability of a stand outbreak, based on a function of the proportion of stand basal area for trees greater than 9 inches in diameter, against a random number. This ensures that in a landscape not all stands will have an outbreak in exactly the same cycles.

Simulating Impacts from Western Spruce Budworm

Impacts from western spruce budworm are simulated using the budworm damage component of the Western Spruce Budworm Model (Crookston and others 1990). It computes damage including decreased growth, mortality, and top kill of host trees as a result of defoliation. The keyword set to initiate a western spruce budworm outbreak is complex.

Four attributes of the stand are individually rated. These include proportion of host, age of the stand, stand structure (1 tier, 2 tier, or 3 tier), and stand basal area. A total rating is computed from the sum of the individual attribute ratings. The possible range of hazard ratings are partitioned into low, moderate, and high classes. The stand hazard rating class is assigned based upon these ranges. A low rating class calls a defoliation table that assigns defoliation percentages by species for each of the years in a 5 year outbreak. A moderate rating class calls a table with defoliation percentages by species for a 10 year outbreak. Finally, a high rating class calls a table for a 15 year outbreak. Outbreaks are allowed in cycles 1, 5, and 9 of a 10 cycle planning horizon. Management activities can change the tree density and the proportion of host, therefore, changing the hazard rating class. Because the user defined variables used to hazard rate stands are calculated prior to management, special after thin variables (Group 2) must be used to indicate if management has occurred and how much impact this event has had on the stand hazard rating. The following example is a very small subset of the keyword set used to determine if the current cycle is an outbreak cycle and if management has occurred and its impact on tree density.

```
COMPUTE         0
TRIGGER = LININT(CYCLE,0,1,2,3,4,5,6,7,8,9,10, &
                 0,1,0,0,0,1,0,0,0,1,0)
CHGBA = ABA / BBA
END
```

The Event Monitor includes a linear interpolation function (LININT) that for any given X value a corresponding Y value will be stored in the variable. In our example, when cycle is equal to 0 in the top line, the value 0 from the next line is stored in TRIGGER. Likewise, when cycle is equal to 1 (top line), the value 1 (next line) is stored in TRIGGER. Using this function, we can flag cycles 1, 5, and 9 with the value 1 that will indicate cycles in which outbreaks can occur.

The Event Monitor also includes predefined variables, some that are computed prior to any thinning event (for example, BBA) and some that are computed after any thinning event (for example, ABA). Our variable CHGBA stores the value of the after thinning basal area (ABA) divided by the before thinning basal area (BBA). If the CHGBA equals 1, then we know that no management has occurred. If the value is less than 1, we know that not only has an event occurred, but we can discern how much impact the management has had on tree density. The following set of keywords illustrates our method of initiating a western spruce budworm outbreak and assigning defoliation levels based upon a stand hazard rating class.

```
IF           0
VARTOT GT 2.99 AND VARTOT LT 6.00 &
CHGBA GT .5 AND &
TRIGGER EQ 1 AND PER_BBA GT 0
THEN
WSBW
DAMAGE
DEFOL     0     9     35.0     .0     .0     .0
DEFOL     1     9     35.0     .0     .0     .0
DEFOL     2     9     40.0     .0     .0     .0
DEFOL     3     9     35.0     .0     .0     .0
DEFOL     4     9     35.0     .0     .0     .0
DEFOL     0     3     15.0     .0     .0     .0
DEFOL     1     3     15.0     .0     .0     .0
DEFOL     2     3     20.0     .0     .0     .0
DEFOL     3     3     15.0     .0     .0     .0
DEFOL     4     3     15.0     .0     .0     .0
DEFOL     0     4     15.0     .0     .0     .0
DEFOL     1     4     15.0     .0     .0     .0
DEFOL     2     4     35.0     .0     .0     .0
DEFOL     3     4     15.0     .0     .0     .0
DEFOL     4     4     15.0     .0     .0     .0
DEFOL     0     8     15.0     .0     .0     .0
DEFOL     1     8     15.0     .0     .0     .0
DEFOL     2     8     20.0     .0     .0     .0
DEFOL     3     8     15.0     .0     .0     .0
DEFOL     4     8     15.0     .0     .0     .0
END
ENDIF
```

In this example, IF the computed hazard rating (VARTOT) is greater than 2.99 and less than 6.00 and the proportion of the basal area remaining after management (CHGBA) is greater than 0.50 and the cycle is equal to 1, 5, or 9 and the proportion of the basal area in host (PER_BBA) is greater than 0, THEN call the western spruce budworm model (WSBW). Hazard rating values between 2.99 and 6.00 indicate moderate susceptibility. Therefore, 10 years of defoqAation will be assigned for each host tree species. If the CHGBA variable is greater than 0.50, that indicates that management activities changed the tree density by less than 50 percent (a 1.00 equals no thinning and a 0 equals a clear cut) and therefore the hazard rating remains at a moderate level. If the CHGBA is less than 0.50, then the management has changed the tree density by more than 50 percent and the condition will be rejected. A subsequent IF/THEN conditional statement is included in the keyword set and the stand will be considered for a low level outbreak due to mitigation of the pest impact by the thinning activity. A total of five conditional IF/THEN statements complete the simulation for western spruce budworm.

Simulating Impacts from Western Pine Beetle

To simulate the impact for pests where no formal submodel is available, we utilize a hazard rating and a simple mortality function. Western pine beetle is specific to ponderosa pine and in this multi-pest scenario it is the only insect impacting ponderosa pine. To model western pine beetle caused mortality we use the same REMD variable as

discussed for the Douglas-fir beetle simulation. The tree density variable (TO_BA) is also used. The SPMCDBH function is used to compute the quadratic mean diameter for ponderosa pine trees greater than 5 inches in diameter.

```
COMPUTE        0
REMD = FRAC(CYCLE/2)
TO_BA = SPMCDBH(2,0,0)
PP_QMD = SPMCDBH(5,10,0,5)
END

IF          0
TO_BA GT 120 AND PP_QMD GT 10 AND REMD EQ 0
THEN
FIXMORT     0      10      .50      10      999
ENDIF
```

Our outbreak trigger consists of the following IF/THEN statement. IF the total basal area of the stand is greater than 120 and the quadratic mean diameter of ponderosa pines greater than 5 inches is greater than 10 and the cycle is even, THEN use the FIXMORT function to kill 50 percent of the ponderosa pine trees in the diameter class of 10 inches and larger. This mortality will occur in the first year of the cycle.

The current keyword file now includes methods for modeling both endemic and epidemic outbreaks and ways to trigger these outbreaks in a stochastic fashion. This is accomplished by setting the RANNSEED keyword to zero at the beginning of the simulation. This will pull a different random number off the computer clock with each stand or replication. (If the RANNSEED is not set to 0, the default will start with the same RANNSEED number each time and mortality will occur in the same cycles each time.) The hazard rating conditions must be met for a stand to qualify for either an endemic or an epidemic outbreak. Two separate triggers and FIXMORT statements are included: one for an endemic and one for an epidemic outbreak.

```
RANNSEED       0
COMPUTE        0
REMD = FRAC(CYCLE/2)
TO_BA = SPMCDBH(2,0,0)
PP_QMD = SPMCDBH(5,10,0,5)
END

IF          0
RANN GT .20 AND TO_BA GT 120 AND PP_QMD GT &
10 AND CYCLE GT 1
THEN
FIXMORT     0      10      .20      10      999
ENDIF
```

In this example, the Event Monitor variable RANN is used to convert the random number to a probability (a number between 0 and 1.00). In an IF/THEN statement, we state that IF that random probability is greater than 0.20 and the total basal area of the stand is greater than 120 and the quadratic mean diameter is greater than 10 and the cycle is greater than 1, THEN kill 20 percent of ponderosa pine trees in the 10 inch or greater diameter class. This simulates mortality associated with an endemic outbreak. Given many replications and meeting all other conditions of the IF, this would occur 80 percent of the time.

To simulate an epidemic outbreak, the same method is used, only the probabilities and the intensity change.

```
IF          0
RANN GT .80 AND TO_BA GT 120 AND PP_QMD GT &
10 AND CYCLE GT 1
THEN
FIXMORT     0      10      .50      10      999
ENDIF
```

In this example, all other conditions remain the same, except the random probability must be greater than 0.80 and the mortality rate is changed to 50 percent of the ponderosa pines in the 10 inch or larger diameter class. Given many replications and meeting all other conditions of the IF statement, this would occur 20 percent of the time. If the second IF statement (epidemic condition) is true, then the first IF statement (endemic condition) will also be true and two FIXMORT activities will be scheduled. It is very important that the sequencing of these remain the same, with the endemic trigger first followed by the epidemic trigger. If this occurs, only the second (epidemic) FIXMORT will be done as long as no value is placed in field 6 of either of the FIXMORT functions for this simulation.

Other Considerations

Currently users of the pest model retrieve a version of their variant with one pest extension linked to it. For example, if you are a Central Idaho Variant user and wish to model western spruce budworm, you would retrieve CID.PR or CID.EXE depending on the computer platform. If you wish to run Douglas-fir beetle, then you would retrieve CIF.PR OR CIF.EXE. To run the multi-pest model, we have linked three pest models (Douglas-fir beetle, western spruce budworm, and mountain pine beetle) to the CI Variant and it is called CIX.PR or CIX.EXE. The submittal system does not support this version. Users can not select it during the submittal set up process. Users are advised to replace the CI, CIF, or CID with CIX but name the program CI. Runs made without the pest keywords will be the same as regular FVS. The keyword file can be inserted using a test editor after submittal or by using the OPEN, ADDFILE sequence of commands in submittal on both the DG and PC/DOS versions. A copy of the keyword file can be requested from Joy Roberts on DG via R04F02A or via e-mail at /s=j.roberts/ou1=r04f02a@mhs-fswa.attmail.com.

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Forest Health Assessment—Piney Analysis Area, Holy Cross Ranger District, White River National Forest

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Abstract—A forest health assessment of lands within the White River National Forest in Colorado utilized the Forest Vegetation Simulator to analyze stand conditions at the landscape level. FVS was used to assess the potential impacts of insect and disease as well as management activities under a number of potential scenarios. Projections of the effects of mountain pine beetle, dwarf mistletoe and root disease were made in conjunction with various stand manipulations in order to portray the range of possible future conditions. FVS, together with SVS (Stand Visualization System), are valuable tools by which potential stand conditions can be portrayed and presented to land managers and to the public.

At the request of the White River National Forest in Colorado and the Holy Cross Ranger District, the forest health of the Piney River and Red Sandstone Area was examined. Located north of the Colorado towns of Avon, Minturn, and Vail, the Piney Analysis Area encompasses three watersheds over more than 85,000 acres, 48,000 of which are forested. Approximately 36 percent (17,360 acres) of the forested National Forest lands in the Analysis Area is in aspen cover type, 31 percent (15,184 acres) is in lodgepole pine cover type, 31 percent (14,956 acres) is in Engelmann spruce/subalpine fir cover type, and 1 percent (601 acres) is in Douglas-fir cover type.

A number of insect and pathogenic organisms play important roles in the ecology of the forests in this area. The analysis that was performed assessed how insect and disease activity affects and will affect current and future stand conditions. Because of the history of mountain pine beetle activity in the lodgepole pine cover type (including a major outbreak in the 1980's), that forest component was chosen for detailed evaluation. Analysis of existing Stage 2 stand exam data (collected from 1976 to 1993) showed that the size class distribution within the lodgepole pine cover type in the Piney Analysis Area predominates toward the larger (and older) tree classes (fig. 1). The data also revealed that the greatest potential threat to the stands of the lodgepole pine cover type was from three mortality agents: mountain pine
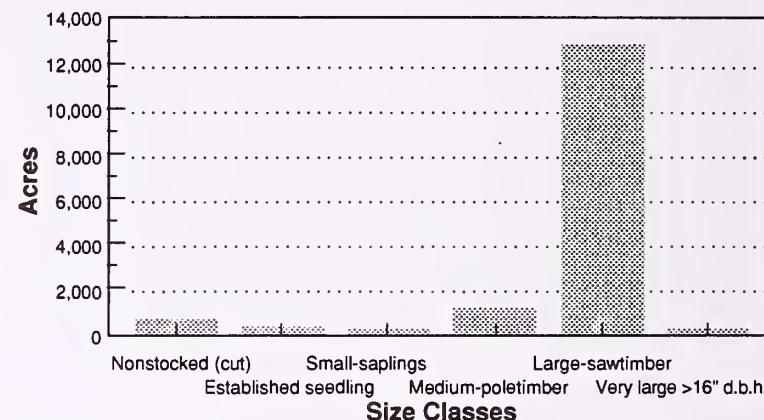
Figure 1—Size class distribution within the lodgepole pine cover type of the Piney Analysis Area.

beetle (*Dendroctonus ponderosae*), lodgepole pine dwarf mistletoe (*Arceuthobium americanum*), and Armillaria root disease (*Armillaria* spp.). A systematic survey was performed in 1994 to assess the current stand conditions and insect and disease levels in the Analysis Area. The Forest Vegetation Simulator (FVS) was then used to project future stand conditions based on these survey results.

Methods

Stand Exam Survey

Although analysis of existing Stage 2 stand exam data (collected from 1976 to 1993) revealed the major insects and diseases affecting the lodgepole pine cover type, it was not sufficient to quantitatively assess their impacts. As a result, a systematic survey was performed, in which 20 percent of the area in lodgepole pine in the analysis area was examined. The survey was designed as a stratified random sample. Stratification was done on the basis of geographic area (North, South, and East), mountain pine beetle hazard rating (low, moderate, and high) and dwarf mistletoe infection (DMI) rating (none, low, moderate, and high). A total of 77 stands, covering 3,218 acres, were chosen for survey. Standard Region 2 stand exam methods were used, but the stand exam forms were modified so that more detailed bark beetle, dwarf mistletoe and root disease data could be taken. The completed data was entered into the Oracle based RMRIS (Rocky Mountain Resource Information System) data base on the Data General and summaries of each stand

were obtained through the RMSTAND portion of the program. Mountain pine beetle risk, dwarf mistletoe infection ratings and root disease severity ratings were calculated for each of the three geographic areas and for the entire Piney Analysis Area. In addition, pest interaction grids, showing the numbers of surveyed acres in each possible interaction of insect and disease (MPB x DM, MPB x RD, and DM x RD), were collated for the entire analysis area.

Forest Pest Model Runs

In order to gain a better understanding of the potential impacts of mountain pine beetle, lodgepole pine dwarf mistletoe, and Armillaria root disease on the lodgepole pine stands of the Piney Analysis Area, a sample of stands were chosen as example stands to simulate the effects of the various insects and diseases over 10 cycles (100 years). Stand growth was simulated utilizing the Forest Vegetation Simulator Version 6.2, Central Rockies Lodgepole Pine Variant. To simulate mountain pine beetle and Armillaria root disease effects, the Mountain Pine Beetle and Western Root Disease pest extension models were used. To simulate dwarf mistletoe effects, the base FVS model was run with and without dwarf mistletoe effects (MISTOFF engaged and not engaged). Nineteen stands from the 1994 survey were chosen as example stands for model runs. To ensure that a wide variety of initial insect and disease intensities were represented, the stands were chosen from the various strata identified from the DM x MPB and DM x Root Disease interaction grids.

The Forest Vegetation Simulator (FVS) was utilized to illustrate the various results from selected model runs. This program produced images which are easy for the lay person to understand and have a great deal of value for public meetings. The use of FVS resulted in a series of images which portrayed such topics as the effects of mistletoe in a stand over time and the effects of bark beetle activity on the long-term forest conditions.

Results and Discussion _____

Stand Exam Survey

Table 1 summarizes the mountain pine beetle risk levels and lodgepole pine dwarf mistletoe and root disease incidence and severity levels that were identified in the 1994 survey. Ninety-six percent of the surveyed area was found to be at moderate to high risk to mountain pine beetle. Elevation was most responsible for differentiating high and moderate-risk stands. Seventeen percent of the total acres had dwarf mistletoe infestation, and 13 percent had moderate to high DMI levels. Over half of the acres (53 percent) had Armillaria root disease, but moderate to high levels were identified on only 19 percent of the acres.

The interactions between mountain pine beetle risk, dwarf mistletoe and root disease incidence at the Piney Analysis Area are shown in table 2. Approximately 18 percent of the acres had both dwarf mistletoe (low, moderate, or high infection levels) and mountain pine beetle (moderate to high risk levels) management concerns. Although approximately 54 percent of the acres in the Analysis Area had both Armillaria root disease (low, moderate, or high levels) and moderate to high bark beetle risk, only 20 percent had moderate to high ratings for both. In contrast, approximately 10 percent of the surveyed acres had both dwarf mistletoe and root disease, but only 2 percent had moderate to high ratings for both.

Forest Pest Model Runs

Mountain Pine Beetle Model Runs—Six stands from the various risk rating classes (low, medium, and high) were selected to be run through FVS under various assumptions regarding mountain pine beetle outbreaks. Using the mountain pine beetle outbreak keywords, outbreaks were initiated within the model at year 10, year 20, and year 40.

Table 1—Mountain pine beetle risk, dwarf mistletoe conditions and root disease conditions for the lodgepole pine cover type of the Piney Analysis Area: 1994 survey.

Total analysis area—3,218 acres, 77 stands, 455 points				
MPB risk rating:		Low:	131 acres (4%),	3 stands (4%)
		Mod:	2,282 acres (71%),	54 stands (70%)
		High:	805 acres (25%),	20 stands (26%)
DMI:	Low	(DMI = 0.1-1.99):	149 acres (5%),	5 stands (6%)
	Mod	(DMI = 2.0-3.99):	290 acres (9%),	10 stands (13%)
	High	(DMI = 4.0-6.0):	121 acres (4%),	2 stands (3%)
	Total	**(All infested areas):**	**560 acres (17%),**	**17 stands (22%)**
RD:	Low	(RD = 1-20%):	1,092 acres (34%),	19 stands (25%)
	Mod	(RD = 21-40%):	186 acres (6%),	6 stands (8%)
	High	(RD > 41%):	434 acres (13%),	14 stands (18%)
	Total	**(All infested areas):**	**1,712 acres (53%),**	**39 stands (51%)**

Table 2—Interactions between mountain pine beetle risk, dwarf mistletoe, and root disease incidence at the Piney Analysis Area: 1994 survey.

1. Dwarf Mistletoe Infection x Mountain Pine Beetle Susceptibility

		Susceptibility to Mountain Pine Beetle		
Dwarf Mistletoe Infection		Low	Moderate	High
None	(DMI = 0)	105	1,779	774
		(3%)	(55%)	(24%)
Low	(DMI = 0.1-1.99)	0	126	23
		(0%)	(4%)	(1%)
Moderate	(DMI = 2.0-3.99)	0	256	34
		(0%)	(8%)	(1%)
High	(DMI = 4.0-6.0)	0	121	0
		(0%)	(4%)	(0%)

2. Root Disease Rating x Mountain Pine Beetle Susceptibility

		Susceptibility to Mountain Pine Beetle		
Stand Root Disease Rating		Low	Moderate	High
None	(0% infected)	105	1,173	228
		(3%)	(36%)	(7%)
Low	(1-20% infected)	0	585	507
		(0%)	(18%)	(16%)
Moderate	(21-40% infected)	0	186	0
		(0%)	(6%)	(0%)
High	(>41% infected)	0	335	96
		(0%)	(11%)	(3%)

3. Dwarf Mistletoe Infection x Root Disease Rating

		Stand Root Disease Rating			
		None	Low	Moderate	High
Dwarf Mistletoe Infection		0%	1-20%	21-40%	>41%
None	(DMI = 0)	1,285	829	145	399
		(40%)	(26%)	(5%)	(12%)
Low	(DMI = 0.1-1.99)	115	34	0	0
		(4%)	(1%)	(0%)	(0%)
Moderate	(DMI = 2.0-3.99)	106	108	41	35
		(3%)	(3%)	(1%)	(1%)
High	(DMI = 4.0-6.0)	0	121	0	0
		(0%)	(4%)	(0%)	(0%)

Low MPB risk—Note: There was no DM in this stand

Figure 2—Stand FVS runs—Piney Analysis Area: predicted volumes under various assumptions.

High MPB risk

Figure 3—Stand FVS runs—Piney Analysis Area: predicted volumes under various assumptions.

Additional runs were made testing the interactions of mountain pine beetle and dwarf mistletoe by using the MISTOFF keyword.

From these runs two generalizations became evident. The first point is that it did not really matter when the mountain pine beetle outbreak was initiated. The greater stand volumes which were accumulated in runs with late outbreak initiation was compensated by greater total volume loss (fig. 2, 3). In other words, the effect of mountain pine beetle outbreak initiation tended to bring stands to a 'base volume level' regardless of when the outbreaks were initiated. These simulations tend to support the idea that mountain pine beetle outbreaks are cyclic events which return stand conditions to earlier successional stages.

The second point illustrated by these runs is that a stand in which a beetle outbreak is initiated relatively early in the run cycle (year 10 or 20 out of the 100 year run) returns to a condition of high risk before the end of the run cycle. Once again, the cyclical nature of mountain pine beetle outbreaks is demonstrated. Although a beetle outbreak removes the larger trees from a stand (thus reducing mean diameter), with the passage of time this size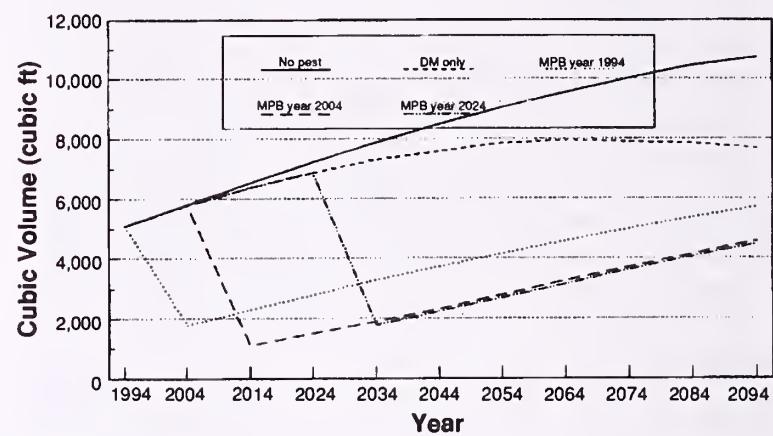 is regained and the mean stand age likewise increases. From a managerial standpoint, the cyclical nature of bark beetle outbreak and risk of outbreak demonstrates a need for periodic stand manipulation to reduce this risk.

Dwarf Mistletoe Model Runs—Nine stands, representing a sample of the stands inventoried with varying degrees of dwarf mistletoe infection, were selected as examples to simulate the effects of dwarf mistletoe. The impact of dwarf mistletoe on cubic volume over the 10-cycle period for three of the stands (low, moderate, and high DM levels) is shown in figures 4 to 6. Overall, the FVS model runs adequately reflected the disease impacts one would expect to see in the field. The reduction in total cubic foot volume of stands infested with dwarf mistletoe ranged from 11.2 to 53.3 percent over the simulation period. As expected, the volume reduction was greatest in stands with the higher dwarf mistletoe ratings.
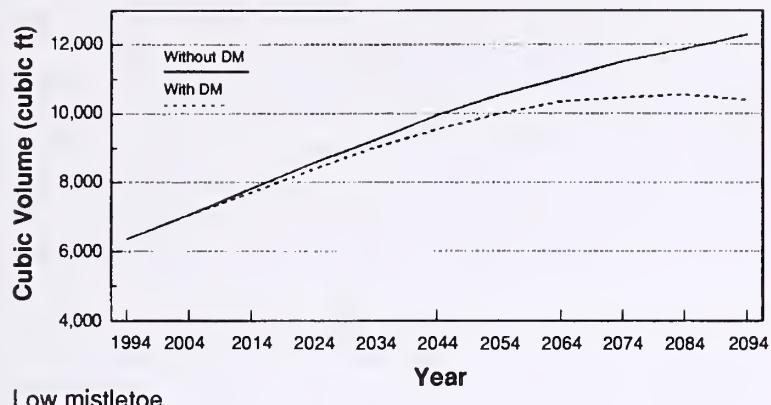
Low mistletoe

Figure 4—Stand FVS runs—Piney Project: impact of dwarf mistletoe on cubic volume.
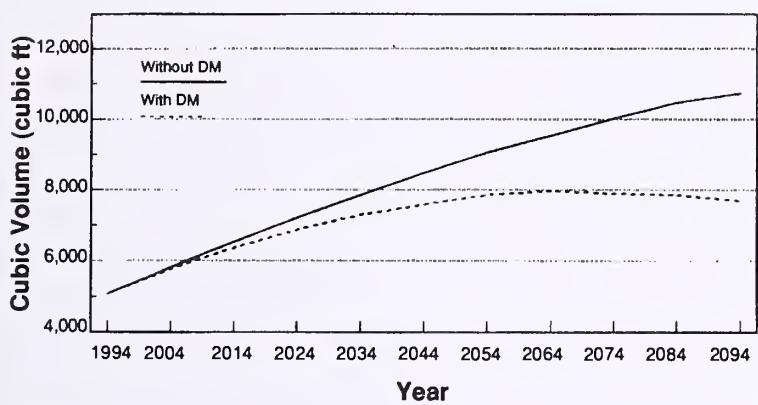
Medium mistletoe

Figure 5—Stand FVS runs—Piney Project: impact of dwarf mistletoe on cubic volume.
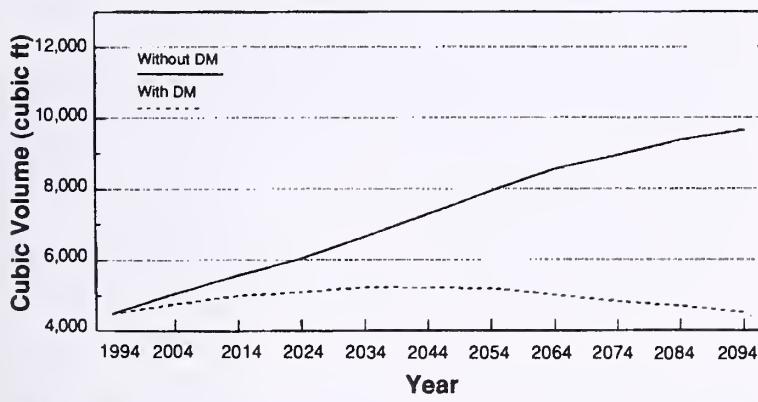
High mistletoe

Figure 6—Stand FVS runs—Piney Analysis Area: impact of dwarf mistletoe on cubic volume.

To further illustrate the impacts of dwarf mistletoe on the lodgepole pine stands in the Piney Analysis Area, a moderately diseased stand was run through the Stand Visualization Simulator (SVS). In dramatic fashion, the SVS program illustrated not only the volume impacts of dwarf mistletoe, but highlighted the impacts on stand composition. In 1994, the 85 year old sample stand contained 85 percent lodgepole pine (on the basis of trees per acre). The remaining 15 percent of trees per acre consisted of a mix of Engelmann spruce and subalpine fir. After 100 years with dwarf mistletoe, the lodgepole pine component dropped to 55 percent, with the remaining 45 percent in spruce or fir. Without dwarf mistletoe (with MISTOFF engaged), the ratio of lodgepole pine to spruce or fir dropped to only 73 percent lodgepole pine and 27 percent spruce or fir. Dwarf mistletoe was thus shown to not only have effects on overall volume, but was also shown to accelerate the shift in stand composition from lodgepole pine to spruce or fir.

Armillaria Root Disease Model Runs—Ten stands were chosen for root disease simulation runs. The percent of sample points with root disease ranged from 0 to 100 percent (low to high). The impact of Armillaria root disease on cubic volume over the 10-cycle period for four of the stands (none, low, moderate, and high RD levels) is shown in figure 7. While running the root disease model, it became evident that the impacts that were reported greatly overestimated the actual impacts of root disease in the sample stands. In all cases (where root disease was present), extensive mortality was reported for all age classes within the first 40 years. This was then followed by either slow continued mortality or slow recovery of the stand. This pattern of mortality is not what has been observed for lodgepole pine in the central Rocky Mountains. Rather, what is expected is greater mortality in
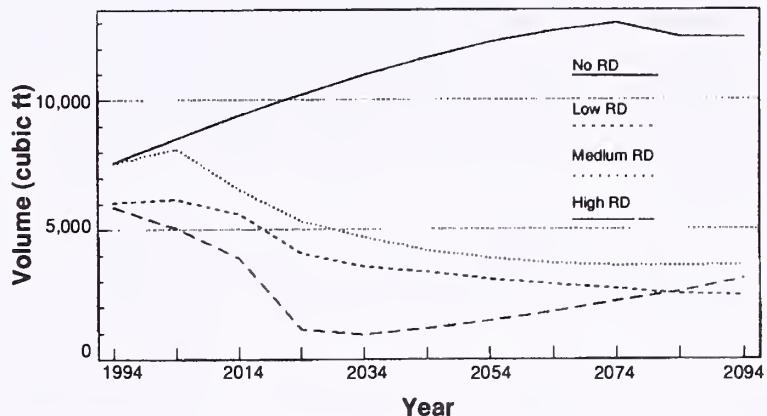
Figure 7—Stand FVS runs—Piney Analysis Area: impact of root disease on cubic volume.

the younger age and size classes, and lessened impacts as stand age increases (Sharon 1988). Because the FVS runs did not reflect the impacts one would expect to see in the field, SVS projections were not run.

Conclusions

The primary function of Forest Health Management is to provide information to managers and the public regarding the health of forest stands. Both FVS and SVS have proven to be effective tools toward this goal. These programs provide a means to project stand conditions into the future under various assumptions, thus allowing managers to consider long-term effects of current management practices. This type of information is especially useful in the arena of public meetings where lay persons are asked to consider the results of current land management practices as much as 100 years in the future.

One point that we stress is that the results of FVS runs are simulations and not predictions. Our public needs to understand that the results of FVS runs should be compared between alternative activities, and should not be used to describe the future condition of the stand. The difference between simulation and prognostication is subtle, but it is important in order to maintain credibility.

The need to periodically manipulate lodgepole pine stands in order to reduce the risk of mountain pine beetle outbreak was dramatically illustrated. Current stand conditions are indicative of high risk to mountain pine beetle outbreak. In 1985 a report on the condition of lodgepole pine stands in the vicinity of the Piney Analysis Area suggested that about "14,000 acres needs to be regenerated each decade" if the lodgepole pine type were to be maintained (Lessard 1985). Since this time only 1,202 acres have actually been regenerated. FVS has demonstrated the need for a greatly increased effort toward achieving the desired stand conditions.

Overall, FVS proved to be an excellent tool to simulate the behavior of dwarf mistletoe in the Piney Analysis Area. The model clearly showed realistic impacts of the disease over the 100 year run period. The SVS program was particularly useful in illustrating these impacts. Through the use of the program, the effects of dwarf mistletoe on future stand structure and composition could be seen much more clearly than was possible from numerical FVS summary tables.

The pattern of mortality by Armillaria root disease that was reported by the Western Root Disease Model did not reflect what has been observed for lodgepole pine in the central Rocky Mountains. In our Region, Armillaria root disease tends to behave as a thinning agent in younger regenerating lodgepole pine stands. Impacts are minimal in pines that are above 30 years of age. Because all of the stands that were run through the Western Root Disease Model were 75 years old or older, we would have expected all of the impact curves in figure 7 to approximate the shape of the "No Root Disease" curve.

It must be kept in mind that the root disease model, as it presently exists, reflects assumptions on root disease spread characteristics that are true for the majority of situations throughout the western United States. In most cases, *Armillaria* spp. affects all size classes and cumulative impacts slowly increase as the root disease centers increase with size. The Forest Health Management staff of the Rocky Mountain Region, together with the Forest Health Technology Enterprise Team, is currently working on improving the model for lodgepole pine. As part of this effort, a network of permanent plots has been established in lodgepole pine stands in western Colorado to track the impacts of Armillaria root disease in young and middle-aged stands. Eventually, the model will be calibrated to better reflect observed behavior.

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Linking Terrestrial, Riparian, and Aquatic Systems Classification: A Case Study with the Deadwood Landscape

M. A. Steele

Abstract—Deadwood Landscape is used as a case study for linking terrestrial, riparian, and aquatic system conditions for land and watershed management planning and implementation. A ground-up approach was used for landscape/watershed analysis to ensure linkage of site specific conditions using an Ecosystem Diversity Matrix. The benefit of this approach allows comparison of adjacent and nested landscapes and practical application.

The Deadwood Landscape encompasses 153,000 acres in west-central Idaho on the Boise National Forest, Lowman Ranger District. The area extends from 3,680 to 7,890 ft elevation and includes a variety of vegetation types that range from lower timberline sagebrush/grass communities to high elevation subalpine fir. Various landscape/watershed analyses were conducted on the Deadwood Landscape and resulted in a series of project areas. Deadwood Ecosystem '96 Project is 44,000 acres. It has begun implementation of silviculture and riparian prescriptions (U.S. Department of Agriculture 1995b, 1996). Deadwood Ecosystem '97 is ready for proposed action which initiates NEPA process (U.S. Department of Agriculture 1983c). Additional annual projects are scheduled.

Ecosystem Diversity Matrix

Ecosystem Diversity Matrices (Haufler 1994) are used to monitor changes in the Deadwood Landscape, selected project areas, or adjacent landscapes These spreadsheet reports are developed in a format that links terrestrial, riparian, and aquatic system functions. The concept is based on inherent variability in the physical environment, as evidenced by different plant and animal communities.

The Ecosystem Diversity Matrix (EDM) can display past, present, and future successional vegetation based on given and known successional trends and responses to various disturbance factors (Steele and Geier-Hayes 1987, 1989, 1992, 1993). The units of measure are displayed as distribution of acres of various plant species composition and structure classes, grouped by site potential. The site potential is based on ecological land classification (habitat types) originally developed by Daubenmire (1966) and extended into central Idaho by Steele and others (1981). The study area is usually a geomorphic unit as defined by the National Hierarchical Framework of Ecological Units. (U.S. Department of Agriculture 1993b, 1994a) In this case, the Southern Idaho Batholith Section (lower part of Section M332A) was used (U.S. Department of Agriculture 1975). Similar habitat types were grouped and described as "Habitat Type Classes" (Haufler and others 1996) which become a potential common link for the terrestrial, riparian, and aquatic systems classification.

Ecological Units of Land Classification

The National Hierarchical Framework of Ecological Units (U.S. Department of Agriculture 1993b) was used to delineate the planning scale. The planning scale was based on ecological objectives and practicality. Land classes include site specific Landtype (100s ha), and progressively larger units, Landtype Associations (100s ha to 1000s ha), and Sections (10s to 1000s km^2). All of these land classes put meaningful site specific characteristics into a landscape perspective. However, the scale selected for the EDM was the Section level. The southern part of the Idaho Batholith Section was selected based on four primary considerations (Haufler and others 1996):

1. Similar biogeoclimatic conditions that influence site potential.

2. Similar historical disturbance regimes that influence vegetation structures and species compositions.

3. To provide sufficient ranges of habitat conditions to assure population maintenance of the majority of native species for a given area.

4. To provide practical application by cooperating landowners.

Forested Systems

The EDM approach has been used in National Forests in Washington, Oregon, and Idaho. The "Forested Systems EDM for the Idaho Southern Batholith Section" (table 1) is "95 percent completed" and can be used with private and public land inventories. The Deadwood analysis used a modified version of the "Forested Systems EDM for Idaho Southern Batholith Section" so as to include U.S. Department of Agriculture, Forest Service, Region 2, 3, and 4 vegetative structural classes (U.S. Department of Agriculture 1992, 1993a).

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Table 1—Sample of the Forested Systems Ecosystem Diversity Matrix.

VEGETATION GROWTH STAGES [1]		Habitat Type Class			
		Dry Ponderosa Pine [2] Xeric Douglas-Fir		Cool, Moist Douglas-Fir	
		Potential Cover Types	Acres	Potential Cover Types	Acres
Grass/Forb/Seedling			32		34
Shrub/Seedling	Low / Med / High	*Pinus ponderosa*	43	*(Pinus contorta)* *(Populus tremuloides)* *(Pinus ponderosa)*	134
Sapling: shrub/seedling	L / M / H	*Pinus ponderosa*	56	*(Pinus contorta)* *(Populus tremuloides)* *(Pinus ponderosa)*	0 / 0
WITH HISTORICAL UNDERSTORY FIRE REGIME		Understory Burn 5-25 Years		Fire Mosaic 5-67 Years	
Small Trees Multi-story	L / M / H	*Pinus ponderosa*	123	*(Pinus contorta)* *(Populus tremuloides)* *(Pinus ponderosa)*	234 / 345

[1] 12 Vegetative Growth Stages defined by RMSTAND rule base with BOISEVSS model: by diameter (d.b.h.), by percent canopy low, med, or high (density), and single or multi-storied stands: (U.S. Department of Agriculture 1992, 1993a).

[2] 11 Habitat Type Classes defined by inherent environmental variability in the physical environment, which influences plant and animal associations (Haufler and others 1996).

The Forested Systems EDM is designed to provide information for inherent characteristics of each Habitat Type Class such as: successional pathways, historical inferences, stand hazards for insect and fire parameters, overstory composition, undergrowth composition, yield capability, and regeneration potential.

Riparian/Wetland Systems

The Riparian/Wetland Systems EDM for Idaho Southern Batholith Section is being developed (table 2). Like the Forested Systems EDM, it too can be used with private and public land inventories (Haufler and others 1996). The Riparian/Wetland matrix uses habitat type classes of adjacent uplands as a broad environmental gradient. Within each Habitat Type Class, shoreline, riverine, and depressional systems (Maxwell and others 1995) can be inventoried by acres or river miles. The shoreline, riverine, and depressional systems represent three basic physiographic settings found in the Southern Idaho Batholith. The geomorphic sub-type is described: shoreline has a lakeshore wetland complex sub-type; riverine has three sub-types based on slope gradient; and depressional has two sub-types: depressional wetland complex (glacial scours/moraine basins) and slopebreak wetland complex (seeps and springs).

For each sub-type, vegetative lifeforms such as: Aquatic, Marsh/Wet Meadow, Scrub-Shrub, Deciduous Forest, and Coniferous Forest (Cowardin and others 1979) are displayed (table 3).

The Riparian/Wetland EDM also notes human induced plant communities such as: those induced or maintained by grazing or human introduced non-endemic plants, which displace endemic plant communities.

Methods

Methods for Forest Systems

The user-input variables for the EDM are acres of vegetative structural stage by habitat type class. A series of data processing procedures are necessary for the user to get the EDM input variables:

1. Timber Stand Examinations inputted and edited in RMSTAND (U.S. Department of Agriculture 1992, 1993a).

2. Uses "Most-Similar Neighbor" where timber stand examinations are not done. This is used so as to have complete coverage of the landscape (Moeur and others 1995).

3. Processed through the Forest Vegetation Simulator (FVS) post processors, Boise Vegetative Structural Stage (BOISEVSS.EXE) and Boise Compute (BOISE.EXE or COMPUTE2.EXE; Teck and Steele 1995). BOISEVSS.EXE uses RMSTAND logic and applies Region 4 old-growth definitions and creates GIS ready data file. COMPUTE2.EXE will extract the predefined habitat type or habitat type class and creates a GIS ready data file.

4. The two GIS data files are associated with the stand polygons. The next step is to query GIS (ARCVIEW) for

Table 2—Simplified Riparian/Wetland Ecosystem Diversity Matrix.

		Temperature Gradient (Adjacent Habitat Type Classes)					
		Douglas Fir		Grand Fir		Subalpine Fir	
		Early Succession	Late Succession	Early Succession	Late Succession	Early Succession	Late Succession
Shoreline Systems	Lakeshore Complex						
Riverine Systems	Steep Gradient Complex (>10% slope)						
	Mod. Gradient Complex (2-10% slope)						
	Flat Gradient Complex (0-2% slope)						
Depressional Systems	Depressional Complex						
	Slopebreak Complex						

Across the X-axis are Habitat Type Classes for the adjacent uplands. This serves as a broad environmental gradient and links riparian communities with terrestrial communities.
Along the Y-axis is Shoreline, Riverine, and Depressional Systems.

acres by habitat type and vegetative structural class. Maps or graphs can be produced showing the distribution of "diversity".

5. The last step is to fit the acres queried in GIS into the Forested Systems Ecosystem Diversity Matrix for Southern Idaho Batholith Section.

Methods for Riparian/Wetland Systems

Riparian/Wetland Systems Ecosystem Diversity Matrix considers habitat as a whole. Bulltrout are one of many indicator species that could be considered. Deadwood Watershed Analysis followed Inland Fish Strategy (INFISH) (U.S. Department of Agriculture 1995b) and Riparian Habitat Conservation Area (RHCA) guidelines. Therefore, Bulltrout surveys were a first approach for considering the use of the Riparian/Wetland EDM. The user-input variables for the EDM are river miles or acres of geomorphic sub-type by Habitat Types Class. A series of data collection procedures for shoreline, riverine, and depressional systems were used in Deadwood Watershed to obtain river miles or acres for EDM:

1. Pre-project surveys including fish habitat information, riparian area conditions, and fish species abundance and distribution by subwatershed by Channel Type (Rosgen 1994).

2. Habitat conditions were characterized by the habitat parameters limiting bull trout productivity: spawning gravel fines (sediment <6mm), large woody debris (per mile), stream shade (percent), pool frequency (per mile) and stream reach (miles). (Overton and others 1995).

3. Selecting priority stream areas (PACFISH, INFISH).

4. Using videography for stream conditions and riparian vegetation to determine area of influence in priority stream areas.

5. Field verification of videography using upland indicators for focus on riparian and aquatic habitat conditions.

6. Input into spreadsheets (EXCEL) and graph habitat conditions and compare to natural conditions.

7. GIS data files are associated with the stand polygons. The next step is to query GIS (ARCVIEW) for miles or acres by habitat type and geomorphic sub-type. Maps or graphs can be produced showing the distribution of "priority areas" or "diversity".

Table 3—Simplified Riparian/Wetland Ecosystem Diversity Matrix—Riverine Systems.

Across the X-axis are Habitat Type Classes for the adjacent uplands. This serves as a broad environmental gradient and links riparian communities with terrestrial communities.

Along the Y-axis are the slope gradient complexes. These are further sorted by vegetation lifeforms: Aquatic, Marsh/Wet Meadow, Scrub-Shrub, Deciduous Forest, and Coniferous Forest.

8. The last step is to fit the acres queried in GIS into the Riparian/Wetland Systems Ecosystem Diversity Matrix for Southern Idaho Batholith Section.

The initial forested inventories were performed independent of the riparian and stream pre-surveys. Linking forested systems with riparian/wetland systems occurred during the stage of field verification of a videography flight over priority areas for bull trout spawning. The silviculturist and fisheries biologist made an association that the priority areas for bull trout spawning were located in one Habitat Type Class, persistent lodgepole, which is a frost-prone environment. This corroborates previous findings that Bull Trout spawning habitat is found in the colder waters (less than 15 °C) (U.S. Department of Agriculture 1996). Continued incorporation of field inventories and riparian and stream surveys into the EDM's will provide a practical means of monitoring these types of relationships with habitat conditions. FVS can provide a means for cumulative effects analysis of long-term down-woody-debris recruitment for aquatic habitats. Shade components are provided in overstory and undergrowth information in the forested systems and riparian vegetation information in the EDM.

Discussion

The EDM for the Idaho Southern Batholith Section was used for Deadwood with three key benefits:

1. To provide a means for managing "wildlife, including fisheries" habitat as a whole, and to veer away from "micromanagement," which at best considers only a few conditions at any one time.

2. To practically organize site specific information for recommendations, implementation and monitoring. For example, the EDM organizes key issues, data and several map layers into a single spreadsheet for a land manager to make decisions and monitor successional change.

3. To provide a practical and meaningful scale from the Idaho Southern Batholith Section for nesting and connecting conditions from other landscapes. For example, the "Ecogroup" is made up of the Boise National Forest, Payette National Forest, and Sawtooth National Forest. Our landbase for which the "Ecogroup" has responsibility is the Idaho Southern Batholith Section. In addition, the "Ecogroup" can best coordinate with major private landowners, adjacent to National Forest.

Conclusions

Terrestrial, riparian, and aquatic components were integrated during the Deadwood planning and implementation phases. During the National Forest Management Act (U.S. Department of Agriculture 1983d, 1994a) phase, existing conditions were evaluated. During National Environmental Policy Act (U.S. Department of Agriculture 1983c, 1996) phase, cumulative effects were an integral part of the analysis process. The results were site specific enough to apply directly to the implementation phase with field validation. By organizing existing and future condition reports in a comprehensive terrestrial and riparian matrix, we can link terrestrial and riparian system functions easily and practically. Forest Vegetation Simulation (FVS) was a major and necessary vehicle for processing the field data for input variables (Teck and Steele 1995; Steele 1995) for these matrices.

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The Westwide Pine Beetle Model: A Spatially-Explicit Contagion Model

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Abstract—The Westwide Pine Beetle Model provides a means to project the impact of 3 pine beetle species in FVS simulations of susceptible landscapes. The model simulates the movement of beetles (contagion) between the stands in the landscape, as well as to and from the forests of the "outside world" beyond this landscape. Incorporating the model's projections of beetle impacts on each stand in a section of the Nez Perce National Forest results in a more rapid loss of pine basal area from the landscape than is projected by FVS alone. This successional change in species composition over time better matches the conditions observed in the real world. The spatial dynamics of the beetle infestation may be observed in the model results, as well as the importance of properly accounting for conditions in the "outside world".

Together, the Forest Vegetation Simulator (FVS) (Wykoff and others 1982) and the Parallel Processing Extension (PPE) (Crookston and Stage 1991) model the growth of trees in stands across an entire landscape. The Westwide Pine Beetle Model simulates the movement of beetles within the landscape and beyond, and projects beetle impacts on each stand. As is shown below, this can increase the realism of FVS vegetation projection in forests that are potentially affected by pine beetles.

The following paper provides an overview of the Westwide Pine Beetle Model. A more detailed technical description is available in Beukema and others (1994). As well, a model user's guide and keyword reference guide are available to assist model users (Beukema and Kurz 1994; Beukema and Robinson 1994).

Objectives

The Westwide Pine Beetle Model (WPBM) was designed to:

- Incorporate the impact of pine beetles on FVS projections of stand dynamics
- Model the shift between endemic and epidemic beetle population levels
- Capture the spatial effects of contagion processes operating in the landscape and beyond
- Simulate three beetle species—the mountain pine beetle (*Dendroctonus ponderosae* Hopkins), western pine beetle (*Dendroctonus brevicomis* LeConte), and *Ips* spp.

The resulting model can support silvicultural planning and pest-management efforts in forests that are susceptible to pine beetles.

Methods

The WPBM was developed through a series of collaborative workshops with entomologists, forest scientists, and potential model users. This workshop approach, based on the protocols developed by Holling (1978) for Adaptive Environmental Assessment, has been used successfully in the development of other forest health extensions to FVS (such as the Western Root Disease Model; Shaw and others 1991). This approach allowed the design and parameterization of the model to benefit from a broad pool of expert knowledge, including the 42 scientists listed in the Acknowledgments.

Model Components

The WPBM uses the Forest Vegetation Simulator (FVS) to project stand development and represent timber management activities. The Parallel Processing Extension (PPE) is used to manage the simultaneous projection of hundreds of stands in a landscape. The Westwide Pine Beetle Model itself simulates the impact of pine beetles and other disturbance agents on each stand, and modifies the FVS tree list to account for these effects.

In addition, the WPBM incorporates within itself a model of all the forest land outside the simulated landscape that is near enough to affect beetle dispersal—the so-called "outside world". The model assumes that the stockable portion of the outside world consists of homogenous forests in a specified condition. It then calculates the quantity of beetles that will disperse between the forests of the outside world and

each stand in the landscape. The calculation is mathematically precise, respects all the spatial variation of the landscape, and is based on the same assumptions about beetle movements as is dispersal within the landscape.

Simulated Beetle Activity

The WPBM projects beetle population levels and forest impacts by conducting the following operations in each year of the simulation:

1. *Calculate the quantity of beetles emerging from infested trees.* This depends on the number and size of killed, strip-killed, or top-killed trees in the previous year; the density of *Ips* infestation in slash; and the number of beetle generations per year.
2. *Simulate the dispersal of beetles between stands, and between each stand and the outside world.* Dispersal depends on the average distance between the source and destination areas, and numerous characteristics of the destination (including total area, basal area and size of host pine, stand basal area, and the condition of individual host trees).
3. *Estimate beetle mortality,* based on the quantity of beetles in each stand, the basal area of host trees, and the proportion of total basal area that is host above a minimum size.
4. *Simulate the selection and attack of individual host trees within each stand.* This depends on the number and condition of host trees in each size class and the density of beetles present in the stand. *Ips* is assumed to attack any available slash before attacking live trees.
5. *Determine the result of each attack* (tree death, strip-kill, top-kill, or pitch-out) based on the quantity of beetles attacking each tree, and the size and condition of the tree.

The WPBM then removes beetle-killed trees from the FVS tree-list.

User Controls

The model user may control all of the model's assumptions about beetle behavior (for example, dispersal distances, reproductive rates, and so forth) by way of FVS-style model keywords. In addition, the WPBM provides a number of pest-management options under user-control. These options include pheromone baiting, use of repelling pheromones, pesticide application, sanitation cutting, salvage cutting, and slash management.

The WPBM user may also activate numerous other disease and disturbance agents, including fire, drought, lightning, other beetles, defoliators, mistletoe, root disease, and stem rust. In the WPBM, these "driving variables" act to kill host and nonhost trees, consume woody fuels, kill beetles, reduce tree health, and create "special" trees that attract more beetles. The driving variables are implemented as simple sub-models that are not intended to replace more detailed independent disturbance and health extensions where such extensions are available. The purpose of these driving variables in the WPBM is to allow the model to simulate, in an approximate manner, the interacting effects of multiple disturbance agents.

The WPBM allows the user to choose from three different assumptions about beetle population levels and host abundance outside the landscape. At the user's discretion, conditions in the "outside world" (beyond the immediate landscape that is simulated in detail) may be assumed to be changing in parallel with changes in the landscape, staying constant in the same condition as the landscape average at the start of the simulation, or varying as prescribed by the user at one or more points in time. These different assumptions will influence the quantity of beetles moving between each stand in the simulated landscape and the outside world.

Finally, the WPBM provides output data on numerous indicators selected by the user. The available indicators include the volume, basal area, and size of beetle-killed trees; the condition of remaining live host trees; an index of beetle population level; the amount of slash and standing dead wood in each stand; the amounts of dead woody material in each of three different decay classes, and so forth. Data on these indicators may be obtained as landscape-averages as well as for each individual stand.

Test Results

The model results shown here are for the Trapper Creek Quadrangle of the Nez Perce National Forest. This is an area of 279 contiguous stands with a total area of about 6,400 acres. At the beginning of the simulations in 1990, lodgepole pine dominates other species in the intermediate size classes, but not in the smaller and larger size classes. All simulations were run for a 100 year time period using a 5 year FVS cycle. The Northern Idaho variant of FVS was used, as is appropriate for the Nez Perce.

Two main alternative scenarios are considered here. In scenario 1, "without beetles", the model is run as if no pine beetles are present in the landscape. That is, the dynamics of each stand are projected by FVS in the usual way.

In the second scenario, "with beetles", the model is run with mountain pine beetles active on host lodgepole pine. Beetles are "initialized" in three stands by labeling five trees per acre in each stand as beetle-killed trees from the previous year. All of the model parameters controlling beetle behavior and impact were set to the default values established for this FVS variant in consultation with many of the entomologists and forest scientists listed in the Acknowledgments. A number of variations of the "with beetles" scenario were constructed by varying the conditions assigned to the outside world. In the baseline variation (used to produce all the maps shown in figure 1), host basal area and beetle population density in the outside world are both held constant at 70 percent of the landscape average value at the start of the simulation. In the subsequent variations (used to produce the graph in figure 2), the outside world is either removed from the simulation or made less attractive to beetles by reducing the host basal area to 50 percent of the initial landscape average, with the beetle population density set to either 50 or 70 percent of the landscape average.

The maps in figure 1 show how the basal area of pine changes over time in each stand in the landscape according to whether or not pine beetle impacts are taken into account. The graphs in figure 1 show the size class distribution of

pine in one sample stand at each point in time. The following effects may be seen:

- The basal area of host pine decreases over the course of the simulations. This is projected to occur as a natural consequence of stand development, even in the absence of pine beetles.
- The decrease in pine basal area is significantly larger and more rapid when the effects of pine beetles are taken into account.
- As stands develop, the remaining pine trees are larger in the absence of beetles. When beetles are present, they preferentially attack larger host trees.
- In the presence of beetles, the fate of a stand depends on its location relative to other stands. The beetle outbreak shown here began first in the northwest section of the landscape; stands here experience a greater early loss of pine.

Figure 2 shows the importance of the outside world to simulation results in the presence of beetles. The loss of pine basal area in the landscape is greatly exaggerated when the simulation is run with no outside world at all. Once beetles in this simulation reach epidemic levels in the landscape, they remain at high levels until essentially all large enough host trees have been eradicated—the artificial world of the simulation provides nowhere else for them to "go". As the outside world is made more attractive to beetles, the rate of pine loss decreases.

Discussion

The results highlight the importance of accounting for pine beetle impacts in projections of susceptible landscapes: expected future conditions are quite different when the likely impacts of beetles are considered. The long-term persistence of old, dense pine stands that is projected in the absence of beetles is not observed in the real world. The more rapid decline in pine basal area, the decline projected by the WPBM when beetles were included in the simulation, appears to be closer to the actual observed course of stand development in these forests.

Moreover, the results show the importance of accounting for spatial effects when dealing with contagion processes. It is clearly unrealistic to attempt to predict the probability that a stand will catch fire without considering the condition and fate of adjacent stands. It is just as

a) 1990

Pine Basal Area
- 0 - 5 (sq.ft/ac)
- 5 - 25
- 25 - 50
- 50 - 75
- 75 - 100
- 100 - 125
- over 125
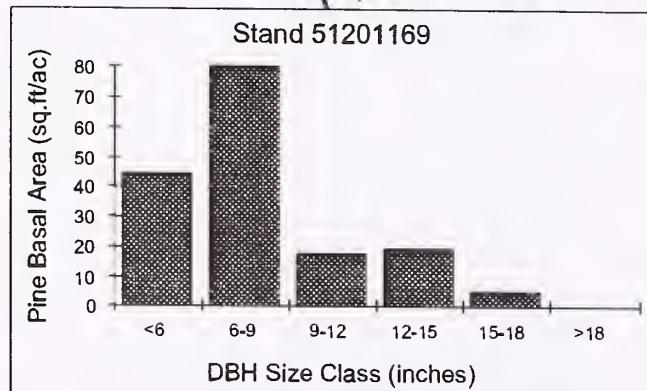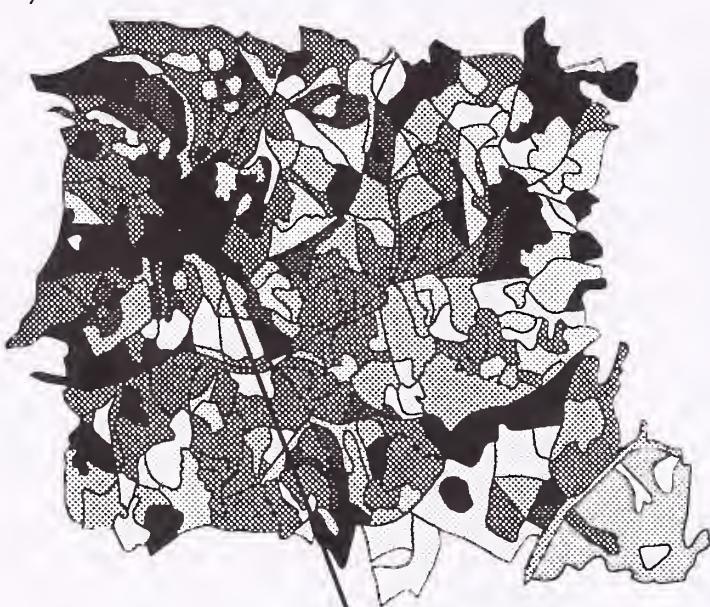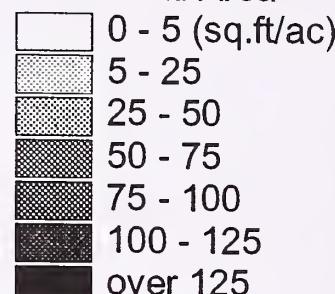
0   1   2 Miles

Figure 1—Projected change in pine basal area in the presence and absence of pine beetles. The maps show the amount of host basal area in each stand in the landscape a) at the start of the simulation in 1990; b) projected for the year 2020 without accounting for possible beetle impacts; c) projected for 2080 without beetles; d) projected for 2020 with probable beetle impacts taken into account; and e) projected for 2080 with beetles. The graphs show the pine size class distribution, by basal area, in the same sample stand in each situation.

b) without beetles 2020
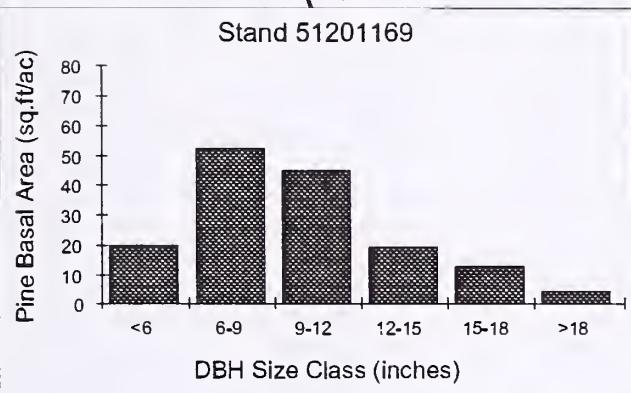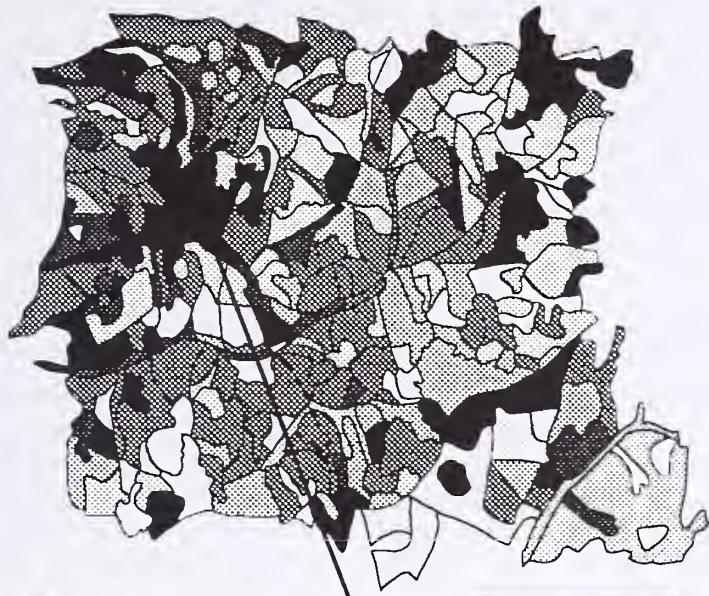
d) with beetles 2020
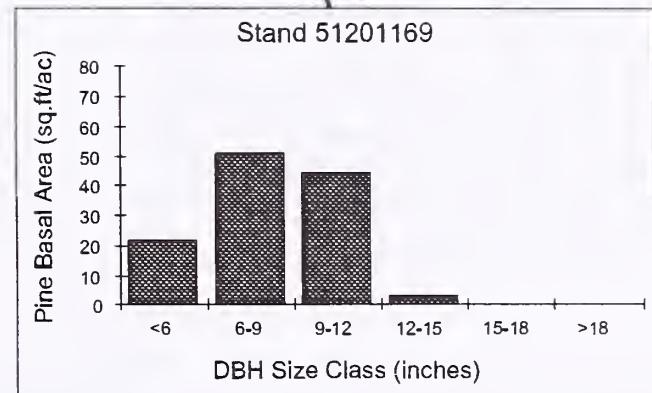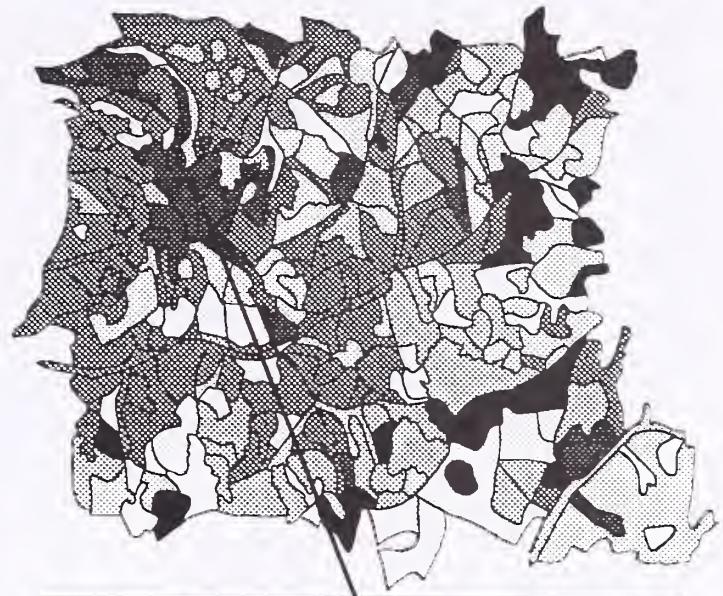
c) without beetles 2080
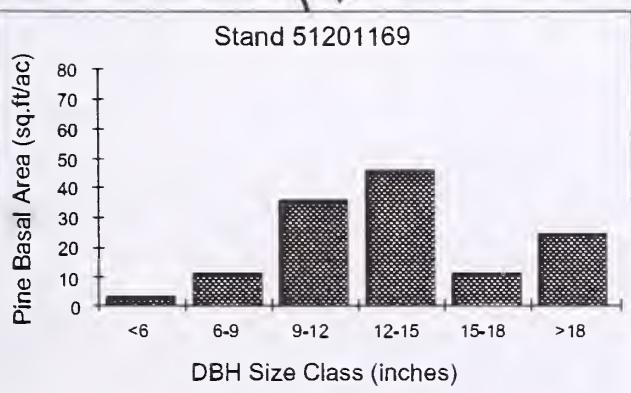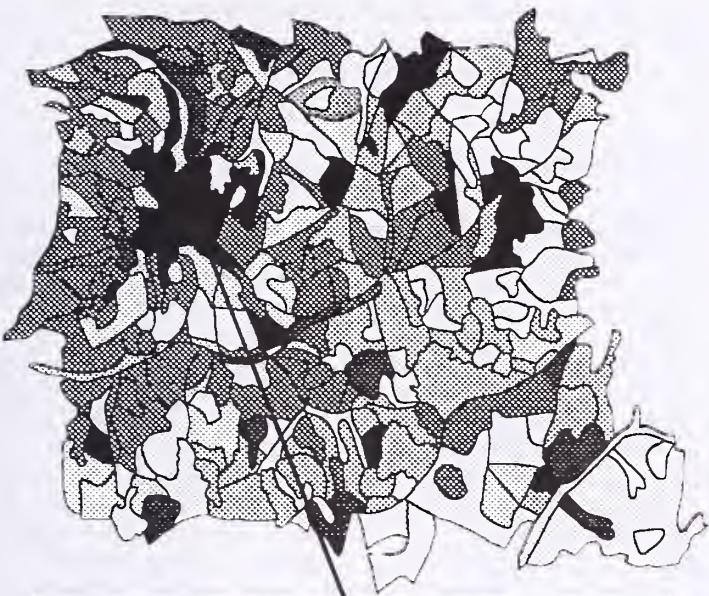
e) with beetles 2080

Stand 51201169

129
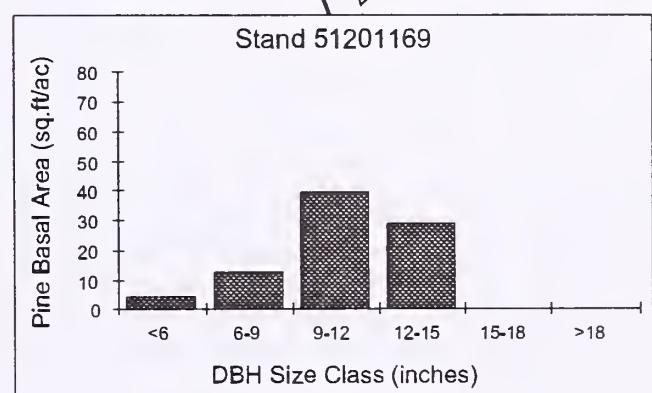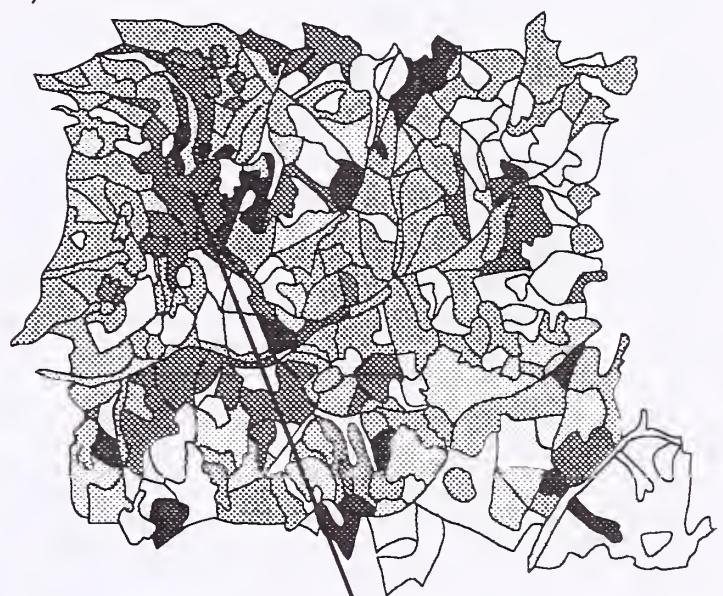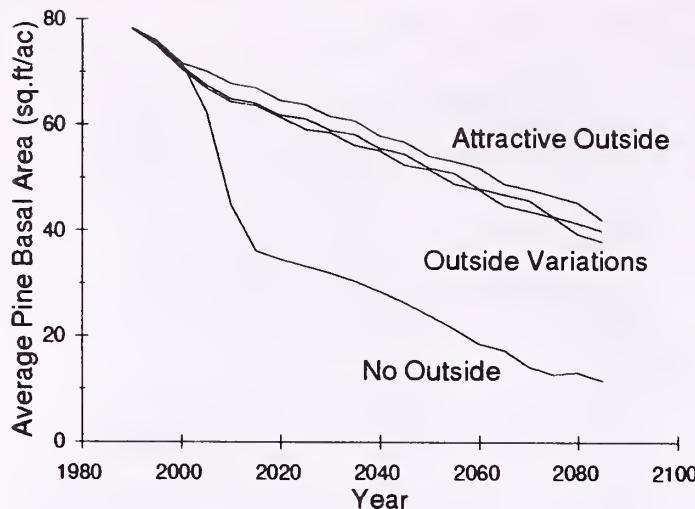
Figure 2—The influence of the "outside world" beyond the simulated landscape. The graph shows how the average pine basal area across the landscape changes over time in the presence of beetles. The lower line shows the decline in pine basal area if the landscape is modeled in isolation (such as if there were no "outside world" beyond the landscape). The higher lines show the results of including the outside world in the simulation, and making that outside world more attractive to beetles by increasing the density of host pine from 50 to 70 percent (top line) of the initial landscape average.

unrealistic to attempt to predict beetle impacts on a target stand without considering the location of that stand relative to sources of infection and concentrations of host trees.

The results also show the importance of accounting for the "outside world" when considering forest insects that can disperse over large distances. The dispersal of beetles within any one landscape—and to and from that landscape—is much influenced by the amount of host available elsewhere. Taking the "outside world" into account allows beetle epidemics to enter endemic phases prior to the eradication of preferred host trees in the simulation. It also helps to eliminate the artificial "edge effects" seen in some simulations, in which stands on the edge of the simulated landscape suffer greater loss of host during beetle outbreaks than do stands in the center.

Because of the importance of the outside world, however, assumptions about its condition can have a strong influence on the results of simulations. The outside world and other aspects of the model require careful calibration to ensure that simulation results will be reliable. The WPBM has thus far undergone only limited testing with landscape-level data sets. As is, the model is suitable for exploring the possible range of outcomes under a given scenario. The WPBM is, in fact, the only modeling tool available for considering beetle effects across a landscape. Ideally, however, the model will receive further calibration before it is used to evaluate alternative scenarios in a management context. Further development of the model awaits the availability of long-term data sets on beetle dynamics and impacts, with information from the stand-level up to the level of the watershed level or higher. The application of these data sets to model calibration would help to ensure the reliability of model projections.

The WPBM demonstrates how both large-scale spatial processes and detailed nonspatial processes may be successfully represented in a single ecological model. FVS and the PPE simulate forest growth and development within each stand in the landscape, while the WPBM accounts for contagion processes between the stands and between each stand and the outside world. The WPBM then calculates the resulting impacts on each stand. This modeling approach may be successfully transferred to simulation of the impacts of other forest insects.

Acknowledgments

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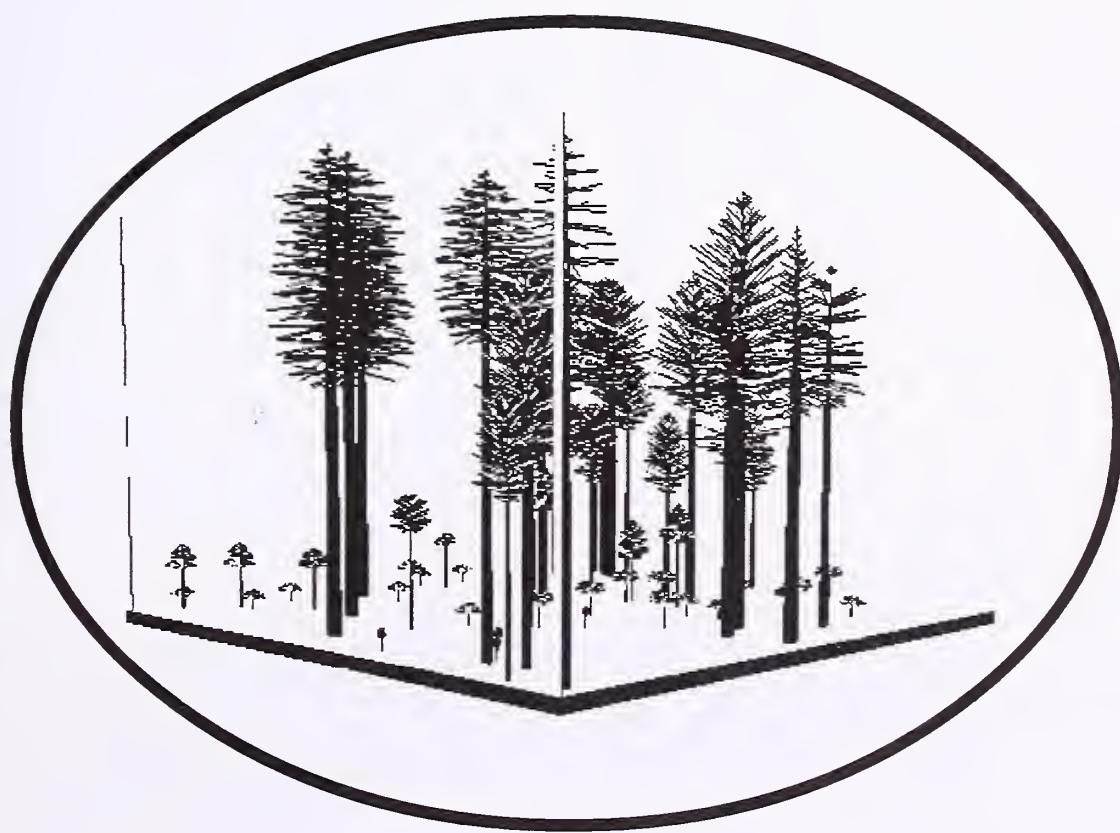
Quantifying Stand Structure Using a Percent Canopy Cover Model (PERCOVE)

Robert J. McGaughey

Abstract—Stand structure, often quantified using the percent canopy cover associated with various structural layers, is an important characteristic used when modeling ecosystem diversity and function. A model is presented, PERCOVE, that classifies individual trees in a stand into structural layers using user-defined rules, models the spatial arrangement of trees, creates a map showing tree crowns, and uses the map to compute an estimate of the percent canopy cover associated with the structural layer. The model, interfaced with the Forest Vegetation Simulator (FVS), can be used to evaluate the structure of existing stands represented by inventory data and stands projected using FVS.

As the focus of forest management shifts from single stands to entire ecosystems, there is an increasing need for methods to quantify stand characteristics in ways meaningful to a wide variety of natural resource disciplines. Stand structure, defined as the spatial distribution of live and dead components in a forest ecosystem, is often used to indicate the status and condition of individual forest stands and their relationship to nearby stands. Schemes to classify stands based on structure attributes vary depending on the intended application of the scheme, scale of the particular analysis project, and stand types involved. Most schemes use measures of species and size class diversity to differentiate stands. Efforts to classify stands based on the percentage of a stand in a given size or age class often rely on the amount of growing space occupied by a structural component, estimated using the percent canopy cover associated with the structural component (for an example scheme see Hall and others 1995).

Canopy cover of an individual tree is defined as the ground area covered by an individual crown as delimited by the vertical projection of its outermost perimeter. Percent canopy cover is an aggregate expression of crown cover expressed as the ratio of ground area covered by tree crowns to the total stand or plot area. Foresters typically use one of several field methods to measure or estimate percent canopy cover. These methods, while suitable for forest inventory, are not well suited for large-area analysis and planning activities where present and future stand conditions must be considered. Such analysis and planning activities often rely on stand projections to analyze future stand or ecosystem conditions. In such cases, direct measurement of stand attributes is impossible.

This paper describes computer software, called PERCOVE, designed to estimate the percent canopy cover associated with user-defined structural layers for stand projection data produced by the Forest Vegetation Simulator (FVS).

Methods for Estimating Percent Canopy Cover

There are many methods suitable for estimating percent canopy cover. However, most rely on measurements taken from aerial photographs or direct measurement of stand characteristics. Such methods generally treat the stand as a whole and cannot be used to estimate the percent canopy cover for individual layers within the canopy without large-scale photography or detailed inventory procedures. These methods cannot be used to estimate the canopy cover for stands whose growth has been simulated to predict conditions not yet realized. Winterberger and Larson (1988) provide an overview of estimation and measurement techniques that rely on aerial photographs and ground measurements. Mueller-Dombois and Ellenberg (1974) provide discussions of several ground-based estimation techniques.

To estimate the percent canopy cover for projected stand conditions, some type of modeling approach is needed. Two methods have been used to model stands to estimate percent canopy cover. First, tree and shrub crown dimensions are used to calculate and sum crown areas to produce an estimate of cover. Such an approach seldom considers possible crown overlap and thus can produce estimates that exceed 100 percent for an individual layer. The second approach involves modeling the geometry and spatial location of individual trees, producing some type of map or image representing the stand, and analyzing the resulting image to estimate percent canopy cover. Van Pelt and North (1996) present a stand-scale crown model designed to quantify stand structure. Their system builds geometric models of a stand using solid shapes to represent trees and tree locations obtained from detailed stand maps to place the tree models. They describe two applications of their model. First, the crowns for all trees can be sliced at specified height intervals and the resulting cross-sectional area and volume calculated for each tree at each interval. These data can then be accumulated to produce estimates of the growing space and percent cover associated with each species at each height interval. The second application attempts to duplicate the photographs produced by wide angle photography using the stand model and computerized ray-tracing (Foley and others 1993). While this modeling approach shows promise for generalized application to a variety of stand conditions, it has only been applied to a few stands where the location of each stem has been mapped.

PERCOVE Overview

The percent canopy cover prediction program, PERCOVE, is designed to estimate the percent canopy cover associated with structural layers contained in a forest stand as represented by a tree list output from the U.S. Department of Agriculture, Forest Service's Forest Vegetation Simulator (FVS). FVS is a stand projection system consisting of an individual-tree growth model that uses common inventory information, growth models that represent other ecosystem components, and tools for simulating management activities. Localized FVS programs, widely used in government agencies and private industry, provide forest managers across the country with a common analytical tool for their unique biological conditions. Tree list files produced by FVS include a record of individual tree diameter, height, species, crown ratio, crown diameter, and tree volume, as well as the number of live, dead, or cut trees per acre and other tree attribute information. The tree list is updated for each projection cycle during an FVS run (Teck and others 1996).

The PERCOVE software applies user-specified classification rules that define structural layers to tree list files produced by FVS to create lists containing each tree in a particular stand layer. The software generates spatial locations for the plants to produce a map showing tree locations and individual, circular plant crowns. PERCOVE then scans the map and calculates a percent canopy cover estimate for the structural layer. Because the spatial location algorithm, described later in this paper, determines where tree crowns overlap, percent canopy cover estimates for each user-defined layer do not exceed 100 percent. The entire process is repeated several times (the number of iterations is specified by the user via a command-line option) and the mean and standard deviation of the percent cover estimates are reported.

A variety of command-line options control the behavior of PERCOVE. Options include:

- General run parameters such as the random number seed, report format, and amount of status information reported
- Stand selection criteria used to select individual stands or projection cycles from FVS tree lists
- Spatial pattern controls such as the sample plot area and overall spatial pattern
- Crown size parameters used to modify crown width estimates reported in FVS tree lists
- Additional parameters to control the number of sampling iterations and the accumulation of dead tree information throughout a stand projection

PERCOVE is designed as a command line utility program for IBM-compatible personal computers running the MS-DOS operating system. No additional software, other than FVS, is needed to use PERCOVE.

Defining Stand Structure Layers

PERCOVE uses simple classification rules to specify characteristics that define the plants contained in each layer of a stand. Rules are created using a collection of keywords, contained in ASCII text files, that are parsed by PERCOVE to build program logic to select individual tree records from the FVS tree list for inclusion in a particular layer. Parameters in a tree list describing individual tree attributes are used to define structural layers. The resulting level of flexibility allows users to define stand layers using a variety of criteria.

There are two types of keywords used to define structure classification rules: keywords that define the overall application of the classification rules and keywords that define the specific criteria used to define an individual layer.

Overall Classification Rule Keywords

Classification rules for each layer are contained within the LAYER—ENDLAYER keyword pair. The LAYER keyword accepts a layer name that will be used to identify the layer in PERCOVE output reports. Each layer definition contains one or more specific classification rules used to identify the trees in the layer. To include a particular tree record from the FVS tree list, the tree record must satisfy all classification rules defined for the layer. Layer definitions are evaluated independent of one another.

The BYPOINT keyword is used to generate percent cover estimates for each sample point contained in the FVS input data. BYPOINT can be placed within a LAYER—ENDLAYER definition to generate estimates using sample points for a single layer or BYPOINT can be placed outside of all LAYER—ENDLAYER definitions to generate estimates for sample points for all layers definitions contained in a rule set.

Specific Classification Rule Keywords

Specific classification rule keywords are provided for all parameters contained in an FVS tree list except the tree and point numbers. Keywords recognized by PERCOVE are shown in table 1.

Keywords, with the exception of SPECIES and NOTSPECIES, require a minimum and maximum value. Interpretation is such that tree records will be included if the tree attribute value is greater than or equal to the minimum value and less than the maximum value. For all relative height keywords: RELHEIGHT, RELCROWNHEIGHT, and RELCROWNLENGTH, interpretation when the maximum value is 1.0 is such that tree records will be included if the tree attribute value is greater than or equal to the minimum value and less than or equal to 1.0. This interpretation is necessary to include the tallest tree in the stand in a particular layer. The SPECIES and NOTSPECIES keywords requires a list of two-letter species codes separated by spaces to be included or excluded from the layer.

Classification Rule Examples

The following set of classification rules defines two layers. The first layer, named UNDERSTORY, includes all trees with diameters less than 3.0 inches and heights less than 35.0 feet. The second layer, named OVERSTORY, includes trees with diameters 3.0 inches and larger and heights 35.0 feet and taller.

Table 1—Classification rule keywords recognized by PERCOVE.

Keyword	Interpretation
TREEINDEX	Select trees based on their tree index
NOTSPECIES	Exclude trees based on their two-letter species code
SPECIESNUM	Select trees based on their species number
SPECIES	Select trees based on their two-letter species code
TREECLASS	Select trees based on their tree class
STATUSCODE	Select trees based on their status code
LIVETREES	Select trees based on the number of live trees per acre for an individual FVS tree record
DEADTREES	Select trees based on the number of dead trees per acre for an individual FVS tree record
DBHINC	Select trees based on their diameter growth rate
DBH	Select trees based on their diameter at breast height
HEIGHT	Select trees based on their total height
RELHEIGHT	Select trees based on their height relative to the tallest tree in the stand
CROWNHEIGHT	Select trees based on the height to the base of the live crown
RELCROWNHEIGHT	Select trees based on the height to the base of the live crown relative to the tallest tree in the stand
HEIGHTINC	Select trees based on their height growth rate
CROWNRATIO	Select trees based on their crown ratio
CROWNWIDTH	Select trees based on their crown width
CROWNLENGTH	Select trees based on their live crown length
RELCROWNLENGTH	Select trees based on their live crown length relative to the height of the tallest tree in the plot or stand
MISTLETOE	Select trees based on their mistletoe damage severity rating
BAPERCENT	Select trees based on their size relative to all trees in the stand
POINTBAL	Select trees based on their size relative to trees from the same sample point
MFTVOL	Select trees based on their merchantable cubic foot volume
FTVOL	Select trees based on their total cubic foot volume
MBFVOL	Select trees based on their merchantable board foot volume
DEFECT	Select trees based on their merchantable defect
TRUNCHEIGHT	Select trees based on the amount of top breakage

```
LAYER UNDERSTORY
    DBH              0.0      3.0
    HEIGHT           0.0     35.0
ENDLAYER

LAYER OVERSTORY
    DBH              3.0    999.0
    HEIGHT          35.0    999.0
ENDLAYER
```

The next set of classification rules divides the stand into species groups. The species identifiers are specific to each variant of FVS (species identifiers in this example are from the East Cascades variant). The SPECIES and NOTSPECIES keywords make it easy to include or exclude species from layer definitions.

```
LAYER PINE
    SPECIES          PP LP WP
ENDLAYER

LAYER OTHER
    SPECIES          WL DF SF RC GF ES AF —
ENDLAYER

LAYER ALTERNATE OTHER
    NOTSPECIES       PP LP WP
ENDLAYER
```

PERCOVE Output

Output from PERCOVE consists of a table showing the percent canopy cover estimates for each layer defined in the classification rules. Output can be produced in an easily read tabular format or a format appropriate for additional processing by other analysis programs. When one iteration is used, only the percent cover estimate is reported. When two iterations are used, the mean percent cover estimate is reported. When more than three iterations are used, the mean and standard deviation of the percent cover estimates are reported.

Generating Individual Tree Locations

One of the primary tasks accomplished by PERCOVE is the generation of spatial locations for individual trees. PERCOVE can generate a variety of spatial patterns:

- Uniformly distributed tree locations
- Randomly distributed tree locations
- Clumped patterns of tree locations with uniformly distributed clump centers

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- Clumped patterns of tree locations with randomly distributed clump centers

For all patterns, a map of individual stem locations is maintained and used to prevent tree stems from being placed on top of one another. Tree crowns can overlap.

Uniformly Distributed Tree Locations

In this method, a grid is superimposed on the sample stand area. The grid spacing is equal to the average spacing between trees calculated as:

grid spacing = SQRT(43,560 / (total stems per acre))

The center of each grid cell is calculated and used as an initial location for a tree. Two variates ranging from –0.5 to 0.5 are generated and multiplied by the grid spacing to serve as maximum offsets in the X and Y directions. The maximum offsets are multiplied by the user-specified randomness factor, ranging from 0.0 to 1.0, to determine the actual offset from the grid center. Locations generated using values of the randomness factor from 0.0 to 0.5 yield patterns in which the grid is obvious. Locations generated using values of the randomness factor from 0.5 to 1.0 have a uniform appearance and the grid structure is not obvious. Figure 1 shows a variety of uniformly distributed stand patterns produced by varying the randomness factor.

Randomly Distributed Tree Locations

This method simply generates uniformly distributed variates ranging from 0.0 to the width of the sample area for the X value and from 0.0 to the height of the sample area for the Y value. Stand patterns created using randomly distributed tree locations can resemble the patterns created using the uniform or clump pattern algorithms depending on the particular controlling factors used to generate the uniform and clumped patterns. By default, PERCOVE uses the same random number seed for each run. Users can specify seed values on the PERCOVE command line or they can specify that PERCOVE use the computer's clock to create a unique seed value. Figure 2 shows a random stand pattern.

Clumped Patterns with Uniformly Distributed Clump Centers

The uniform-clump method generates "clump centers" using the same technique used to generate uniformly distributed tree locations. Individual trees are then randomly assigned to a specific clump. The number of clumps, or clump frequency, can be controlled using command line options in PERCOVE. The clump spacing is calculated as follows:

clump spacing = SQRT(43,560 / (stems per acre * clump frequency))

Individual tree locations within a clump are created by generating a random angle ranging from 0.0 to 360.0 degrees and a magnitude calculated as follows:

magnitude = (random number from 0.0 to 1.0) * clump radius

(A) (B)

(C) (D)

Figure 1—Uniformly distributed tree locations for 100 trees generated using values for the "randomness factor" of 0.25 (A), 0.50 (B), 0.75 (C), and 1.00 (D).
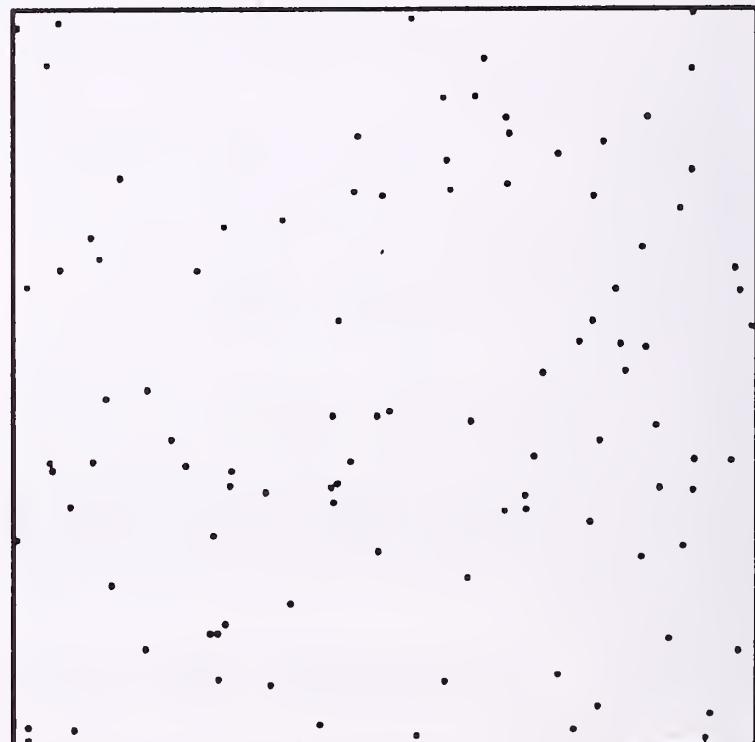
Figure 2—Randomly distributed tree locations for 100 trees.

where clump radius is computed using the following equation:

clump radius = (1.5 – 1.4 * clump density factor) * clump spacing

The random angle and the magnitude are used to offset the tree location from the clump center. This method results in clumps with a radius equal to one and one-half times the clump spacing when the clump density factor is 0.0 and one tenth of the clump spacing when the clump density factor is 1.0. Figure 3 shows the effect of the clump density factor. In figure 3, the clump frequency was 0.25 resulting in 25 clump centers and the randomness factor was set to 0.5.

Clumped Patterns with Randomly Distributed Clump Centers

The random-clump method generates clump center locations using the same method used for randomly distributed tree locations. Individual tree locations within each clump are generated using the same technique used for uniform-clumped patterns.

Example

The following example is intended to show the general function of the PERCOVE program. It does not use all classification rule keywords and is not intended to illustrate the complex classification rules that may be necessary to adequately classify stand structure.
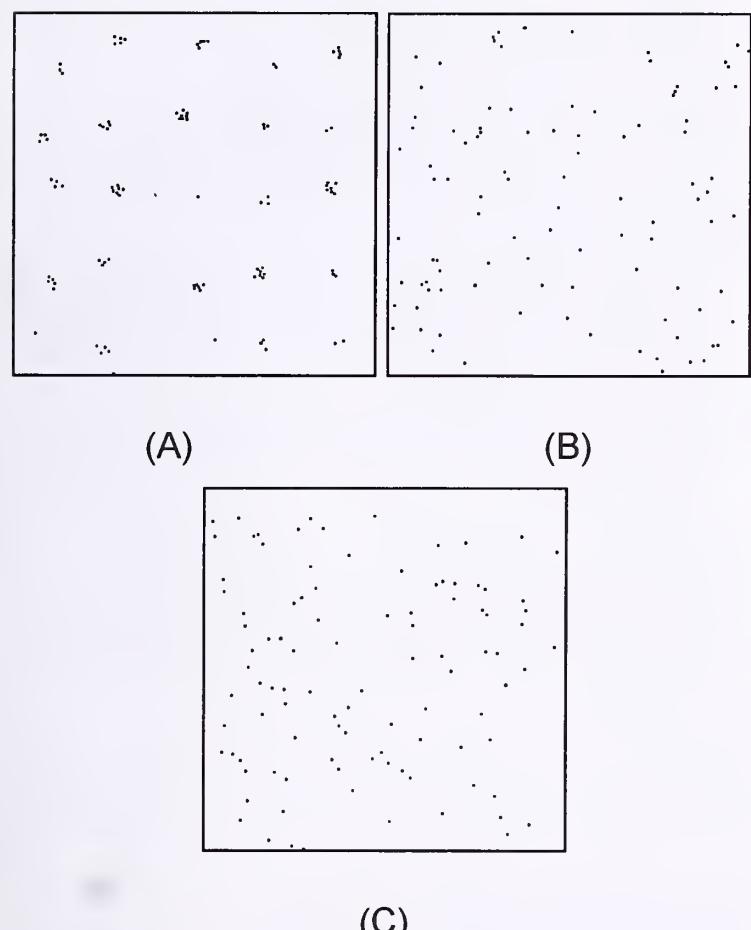
The stand selected for this example is composed of a sparse mixed-conifer overstory with dense lodgepole pine regeneration. The stand inventory data, collected in 1992, was projected using FVS to simulate stand conditions in the year 2032. The projected stand contains 94 square feet of basal area and 2,100 stems per acre. Average tree diameter (d.b.h.) is 2.1 inches (diameters range from <1.0 to 19.0 inches). Average tree height is 15.0 feet (heights range from 7 to 80 feet). Figure 4 shows average stand conditions in 1992 and 2032 as seen in cross-sectional views produced using the Stand Visualization System (McGaughey 1997). Note that in figure 4 individual tree locations are not maintained from 1992 to 2032. The cross-sections, therefore, show changes in overall stand conditions rather than the growth of individual trees.

The classification rules developed for this example, shown in figure 5, divide the stand into three structural layers based on relative tree heights using the RELTREEHEIGHT classification rule keyword. The first layer, named UNDERSTORY, contains trees with relative heights ranging from 0.0 to 0.2. The second layer, named INTERMEDIATE, contains trees with relative heights from 0.2 to 0.6. The third layer, named OVERSTORY, contains trees with relative heights from 0.6 to 1.0. A fourth layer definition, named ALL, contains all trees in the stand (relative heights from 0.0 to 1.0).

Portions of the PERCOVE output describing percent canopy cover estimates for 1992 and 2032 are shown in figure 6. Notice that the sum of the percent cover estimates for the UNDERSTORY, INTERMEDIATE, and OVERSTORY layers does not equal the estimate for the ALL layer (entire stand). This is expected since tree crowns in the different layers will undoubtedly overlap.

(A)

(B)

(C)

Figure 3—Clumped tree locations for 100 trees generated using uniformly distributed clump centers and values for the "clump density factor" of 1.00 (A), 0.50 (B), and 0.25 (C).

(A)

(B)
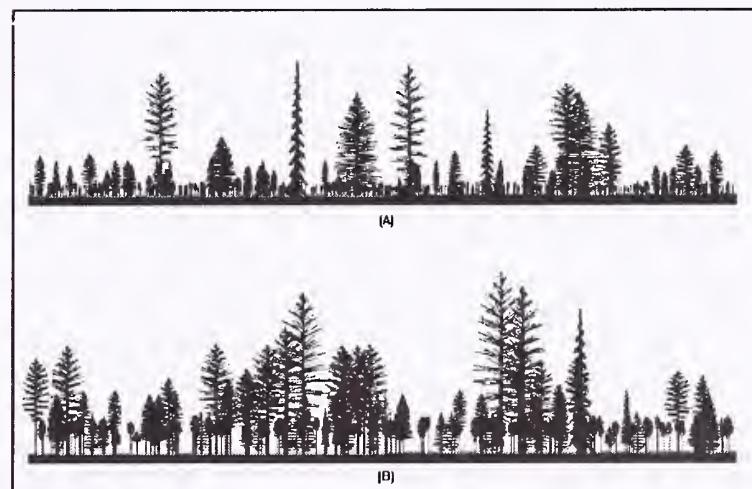
Figure 4—Cross-sectional views of the sample stand representing stand conditions in 1994 (A) and 2044 (B) produced using the Stand Visualization System.

LAYER UNDERSTORY RELHEIGHT ENDLAYER	0.0	0.2
LAYER INTERMEDIATE RELHEIGHT ENDLAYER	0.2	0.6
LAYER OVERSTORY RELHEIGHT ENDLAYER	0.6	1.0
LAYER ALL RELHEIGHT ENDLAYER	0.0	1.0

Figure 5—Example layer classification rules used with PERCOVE.

Stand: 5104.00   Mgmt: NONE   Cycle: 0 Year: 1992

Layer name	Point num	Percent mean	cover sd
UNDERSTORY	—	2	0.0
INTERMEDIATE	—	3	0.1
OVERSTORY	—	8	0.9
ALL	—	12	0.6

Stand: 5104.00   Mgmt: NONE   Cycle: 4 Year: 2032

Layer name	Point num	Percent mean	cover sd
UNDERSTORY	—	7	0.1
INTERMEDIATE	—	22	0.6
OVERSTORY	—	21	5.6
ALL	—	42	3.9

Figure 6—Percent canopy cover estimates output from PERCOVE for the example stand in 1992 and 2032.

Summary and Future Work

As forest managers struggle to understand and plan for the response of entire ecosystems to natural disturbances and management activities, they need repeatable methods to measure stand attributes. PERCOVE provides a suitable method for estimating the percent canopy cover given data describing stand conditions. Such estimates, critical for the consistent application of stand structure classification schemes, allow planners to better utilize results from stand projection systems like the Forest Vegetation Simulator.

The PERCOVE software is currently being tested by several users in government agencies and private industry. Field work is planned for 1997 to further validate the estimates produced by PERCOVE and to calibrate the spatial patterns produced by PERCOVE with directly measurable stand characteristics.

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Using FVS to Provide Structural Class Attributes to a Forest Succession Model (CRBSUM)

Albert R. Stage

Abstract—The Forest Vegetation Simulator (FVS), coupled with a new key to structural classes, provided an empirical link between the Columbia River Basin SUccessional Model (CRBSUM) and the real world. The essence of CRBSUM is a set of residence times and disturbance probabilities for each class (Structural Class, Potential Vegetation Type, Species Type). The concatenation of structural class with species type and potential vegetation type resulted in numerous possible transitions that were subjectively defined. FVS was used to project sample stand inventories to provide objective estimates of the CRBSUM transition times. The FVS runs also provided estimates of timber volumes that would be affected by the disturbances scheduled into the CRBSUM scenarios.

Forest succession can be modeled at two different degrees of resolution, either as an area moving through a sequence of developmental stages, or as a collection of individual plants changing through birth, accretion, and death. This paper describes how models at these two extremes were linked to support a broad-scale planning project for the Columbia River Basin in the Northwestern United States. The successional pathway model (Columbia River Basin SUccessional Model-CRBSUM) was developed by Keane and others (1996) for the Interior Columbia River Basin (ICRB) Scientific Assessment. The individual-tree model is the U.S. Department of Agriculture, Forest Service's Forest Vegetation Simulator (FVS). The FVS modeling system is documented in the scientific literature as the Prognosis Model for Stand Development (Stage 1973; Wykoff and others 1982). However, along with its numerous geographical variants developed and maintained by the U.S. Department of Agriculture, Forest Service, Timber Management Service Center in Fort Collins, CO, the system is known collectively as FVS (Teck and others 1996).

The ICRB is a project of the U.S. Department of Agriculture, Forest Service, and the U.S. Department of the Interior, Bureau of Land Management. Their objectives were to develop an ecosystem management strategy and to implement a watershed conservation strategy for anadromous fish habitat in the ICRB area encompassing about 800,000 km^2. A significant constraint on the analysis was that the project would not fund field data collection. Thus, most of the analysis had to rely on existing information. The significant research task was to provide procedures for translating this existing information in forms useable in the ICRB Assessment.

CRBSUM was devised to represent the future development of all vegetation in this assessment area in a spatially explicit way. Its formulation was constrained by the immense computational requirements of modeling such a large area. This purely conceptual model is given substance by users who must supply all quantitative information on the rates of processes to be represented. CRBSUM sees the world as a collection of pixels characterized at the start of simulation by Potential Vegetation Type (PVT), Structural Stage (SS), SAF Cover Type (species), and Successional Age (SA) (Oliver 1981; Oliver and Larson 1990; O'Hara and others 1996). The status of SS, Cover Type, and SA for each pixel is changed by CRBSUM as the simulation progresses.

Successional pathways and disturbance pathways (fire, insects and pathogens, and management treatment) are defined by the user. In the absence of disturbance, the transition to the next class is accomplished when the successional age exceeds the value set for the particular combination of structural stage, species type, and potential vegetation. Some of the structural stages may have no successor. From them, the only exit is the consequence of disturbance. Disturbances are modeled by pathways that are selected stochastically according to user-defined probabilities. Disturbance may also advance or retard the successional age of pixels. Thus, in the absence of disturbance, successional age and chronological age proceed at the same pace. However, disturbance can advance or retard the successional age relative to chronological age.

To execute the CRBSUM model, users must supply estimates of numerous transition ages and probabilities. Unfortunately, bringing scientific experience to the entire system is difficult because no prior experience exists with the recently defined Structural Stages, and some ecosystems have been studied only rarely. Therefore, no objective data exist based on repeated observation of progression along the possible successional pathways. A PC-based software system, the Vegetation Dynamics Development Tool (VDDT), proved invaluable for eliciting the subjective basis of CRBSUM from technical experts in a workshop setting (Beukema and Kurz 1995a).

Quantitative empirical data on stand development and on successional rates and pathways were already available in the FVS system. Many of the insect and pathogen effects are represented in the various pest extensions maintained by the Forest Service's Forest Health Technology Enterprise Team. This empirically based collection of information, although relevant, is not in a form that is useable by CRBSUM because of inventory and computation limitations

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imposed by the vast, unprecedented geographic scope of the assessments.

The objectives for this endeavor were:

1. To bridge the gap between the information base represented in the FVS system and the information required to execute CRBSUM by providing benchmark estimates of the residence times based on simulations with the FVS system.

2. To provide a procedure for estimating effects of disturbances on the standing biomass, and merchantable volumes removed.

3. To evaluate whether the successional and disturbance pathways defined subjectively in the several ICRB workshops can be replicated using actual inventory data and the FVS system; or conversely, whether the results suggest the need for additional refinement in the FVS system.

4. To develop more effective rules for translating FVS tree lists into the Structural Classes defined by O'Hara and others (1996). (Note: In defining the parameters of CRBSUM, workshop participants equated the Structural Stages of CRBSUM to O'Hara and others' Structural Classes. O'Hara and his co-authors deliberately rejected the term "stage" because they did not presume a particular sequence of transitions. Hereafter, I will use the term Structural Class.)

Partial results of this study were presented at the IUFRO 20th World Congress, Tampere, Finland (Stage and others 1995). Further refinements in the classification rules are presented here.

Calibration of Residence Times ___

Specific steps were:

1. Prepare an FVS postprocessor to classify tree list into SAF Cover Type and Structural Class. (The Structural Class part of this postprocessor has now been incorporated into the FVS base model.)

2. Obtain stand inventories in FVS format.

3. Run FVS for a range of site conditions: Potential Vegetation Type, geographic location, slope, aspect and elevation; for even-aged natural regeneration predicted by the Regeneration Establishment module of FVS, and for existing inventories to produce tree lists and volume summaries for each decade in a 300 year projection.

4. Process tree list output through the classifier.

5. Compute means and variances of residence times for transition from one class to the next.

6. Review transitions in relation to CRBSUM pathways defined subjectively.

7. Repeat steps 3 through 6 for effects of disturbances, including silviculture, fire, insects, and pathogens represented in the FVS system.

Classification Rules _____

Key attributes defining the Structural Classes are the number of distinct crown strata (age cohorts) in the stand and the sizes of trees in the uppermost stratum (table 1).

The Stem-Exclusion class is further divided into two classes—Open Canopy and Closed Canopy. This split must rely on the Potential Vegetation Type because the lack of

Table 1—Definition of structural classes.

Number of strata	Diameter size class of uppermost stratum		
	Seedlings/ saplings <5 inches	Pole/small/ medium trees 5 to 25 inches	Large trees >25 inches
1	Stand initiation	Stem exclusion	Old forest- single stratum
2	Not applicable[a]	Understory reinitiation	Old forest- multistrata
3+	Not applicable	Young forest- multistrata	Old forest- multistrata

[a]This cell could be used to describe regeneration with scattered seed-trees with only a small addition to the classification rules.

understory in the Open Canopy Stem Exclusion class is attributed to below-ground competition. Otherwise, a recent thinning could cause the stand to be classified as Stem Exclusion Open Canopy in Potential Vegetation Types that would not preclude regeneration in openings.

At least three sets of rules purport to classify a tree list into the same set of structural classes. The first set by Latham (1996, chapter 1) uses the proportion of crown areas within traditional classes of diameter at breast height (d.b.h.)—seedlings and saplings, poles, and small, medium, and large trees. I abandoned this approach after evaluating its behavior through the course of projected stand development. (These rules are the ones evaluated by Scharosch and Steere [1995] and reported by Warren and others, this proceedings.) Apparently Latham also experienced difficulties because her chapter 2 outlines a set of rules based on tree height and crown length much like those in Stage and others (1995). Both rules depend on trees being sorted by total height. There are, however, significant differences.

Stage and others (1995) define strata by discontinuities in the structure of crown profiles. Our rationale was that photo-interpreters could only define number of crown strata if separations between the canopy layers were clearly visible. Latham (1996) uses stratum boundaries defined by tree height in relation to the height and crown length of the tallest tree in each stratum. Figure 1 shows the crown cover distribution of a single cohort of trees changing through time. The structure classification for the mid-aged stand applying Latham's rules is perverted because the fixed boundary of the size classes used for classification divides the cohort into what the rules see as two strata. The same problem seems to apply to Latham's height-based rules. I presume that each of our rules leaves room for improvement.

Application of CRBSUM starts with a map created by remote sensing, but without a second-stage sample of ground-based inventories to estimate attributes of the remotely sensed strata. To be consistent with this procedure, we viewed the tree lists generated by FVS as we thought they would appear to a photo interpreter—in terms of crown cover and tree height. Crown area was estimated for each tree in the list using equations developed by Moeur (1981) for which there has been some testing against photo-based data (Moeur 1986). The tree list was then sorted by tree height from tallest to shortest.
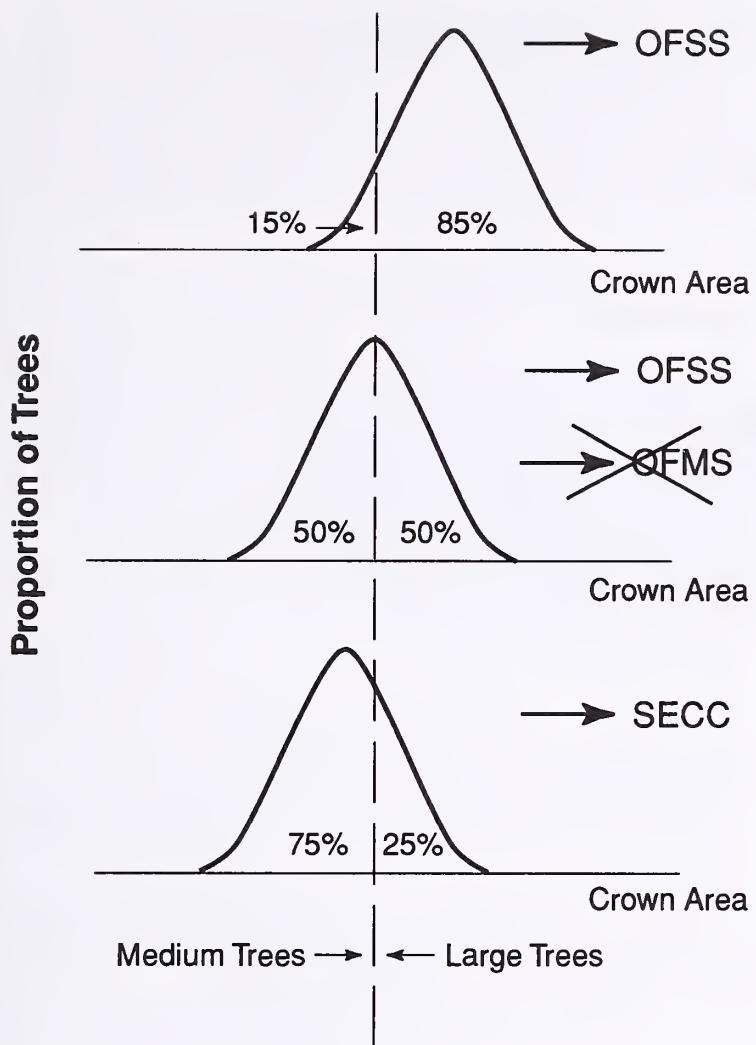
Figure 1—Example of illogical sequence of classes as a single cohort of trees grows across an arbitrary size boundary. The middle diagram would be misclassified as a Multistrata stand using rules that divide strata on the basis of size rather than discontinuities.

Figure 2—Rule for finding discontinuities in height distribution to bound strata.

Bounding the Strata

Discontinuities in the vertical crown structure of the sorted list were defined by Stage and others (1995) as follows: A tree was marked as being the potential top of a lower stratum if its top was lower than the top of the **preceding** taller tree by more than 30 percent of the height of that preceding tree in the list (fig. 2). In our forests, dominant trees in closed stands typically have crowns of about 40 percent of total height. Therefore, the 30 percent criterion would translate into a penetration by the shorter tree into the lower quarter of the next taller tree's vertical crown extent.

Next, the list of potential gaps was sorted, and the two largest gaps were evaluated as bounds of three potential strata. Total crown cover represented by the tree records in a potential stratum must equal or exceed 5 percent of ground surface area to be considered a valid stratum. This cutoff was selected to agree with the instructions given to the photo interpreters. Size of trees in the dominant stratum was calculated by finding the tree record at the 30th percentile in the distribution of crown cover. The mean d.b.h. of the nine

tree records centered on the 30th percentile record in this sorted list defined the size assigned to the stratum. The 30th percentile was chosen instead of the 50th percentile because larger trees are more readily visible from above.

In this process of defining gaps in the crown structure, it was important to ignore tree records that would otherwise span a gap but that represent an insignificant number of trees in the stand—either because of mortality or harvest of the class the record represents. Because the absolute magnitude of this threshold will vary with the sampling intensity of the stand inventory, two criteria were used to ignore inconsequential records. A tree record was ignored if the record represented less than 0.001 trees per acre or if the tree record represented less than 0.01 times the representation of the previous tree. (Note that most sampling rules produce lists in which the number of trees represented by a record increases as tree size decreases.)

When one traces the stand's dynamics using objective rules for classifying a stand into one class, stands may cross and re-cross some class boundaries. This behavior is attributable to the discrete nature of the classification rules. A stand that "walks the boundary" may alternate classes that are intended to be successional. This anomaly may be resolved by insisting that any retrogressive transition require a substantial transgression (see appendix for an algorithm to handle retrogressions).

Bill Wulf, a silviculturist of the Clearwater National Forest, applied the algorithm as it was defined for the ICRB analyses to a large number of stands in his area (personal communication). He found that many stands were being classified as single stratum because no discontinuities were identified. However, many of these stands had what appeared to be true all-aged stand structures. Apparently, what was coming through as a single stratum was, in reality, a collection of many age-classes with little segregation. As a result of this experience, we have added an additional rule to improve the fidelity of the classification to the original concepts. If the tallest tree is larger than the d.b.h. cutoff for

the Old forest-Multistrata class **and** the shortest tree is less than 3.0 inches d.b.h., then the stand is assigned to a Multistrata class.

Transition Times

Estimates of the rates of stand development supplied to CRBSUM are based on a classification of the FVS tree list at each decade into one of the seven structural classes and into the applicable SAF Cover Type. This classification is executed as a postprocessor to the FVS simulation model. As a particular stand simulation is analyzed by the postprocessor, if a stand moves from one class to another class, the transition to the subsequent class is recorded in a matrix of all possible transitions from one class to another. In this matrix, the rows correspond to the source class and the columns correspond to the receiving class. For seven Structural Classes and 10 Cover Types, the matrix can contain 4,830 possible transitions! Within the cell corresponding to an observed transition, the time remaining before a transition to the subsequent class is accumulated. When all stands have been so processed, the means and variances are summarized for each cell.

Development of an example stand generated by the Regeneration Establishment Model (Ferguson and Crookston 1991) in the cedar/hemlock Potential Vegetation Type is illustrated at 30 year intervals in figures 3 through 7, which were drawn by the Stand Visualization System (McGaughey

1997) from tree lists generated by FVS. The classification algorithm applied to the list of trees at 10 year intervals in the simulation showed five transitions: Nonforest, Stand Initiation (residence time = 10 years), Stem Exclusion (50 years), Understory Reinitiation (20 years), back to Stem Exclusion (30 years), and finally to Old Forest Single Stratum (30 years plus).

Volume Estimation

The FVS simulations also estimate volume of the stand and of any scheduled removals at each decade throughout the stand simulation. The question was raised whether these simulations could be analyzed to provide CRBSUM with estimated harvest volumes. There were, however, two major obstacles: (1) CRBSUM does not provide consistent successional ages for all pathways into a Structural Class/PVT cell, and (2) the inventory data used to initiate the simulations do not consistently provide stand ages. These obstacles were overcome by noting that CRBSUM stores the time remaining before transition to the next class along the successional pathway for each pixel. This variable provided a crude "age complement." Thus, volumes per acre provided by the FVS simulations were tabulated by years remaining in the class for subsequent merging with CRBSUM output.

Harvest disturbances were grouped into four types: (1) complete stand harvest or partial harvest, which in turn

Age = 10
Structural Stage = Stand Initiation

Figure 3—Example of Stand initiation Structural Class based on classification of the Forest Vegetation Simulator tree list at 10 years.

Figure 4—Example of Stem exclusion Structural Class based on classification of the Forest Vegetation Simulator tree list at 40 years.

Figure 5—Example of Understory reinitiation Class based on classification of the Forest Vegetation Simulator tree list at 70 years.
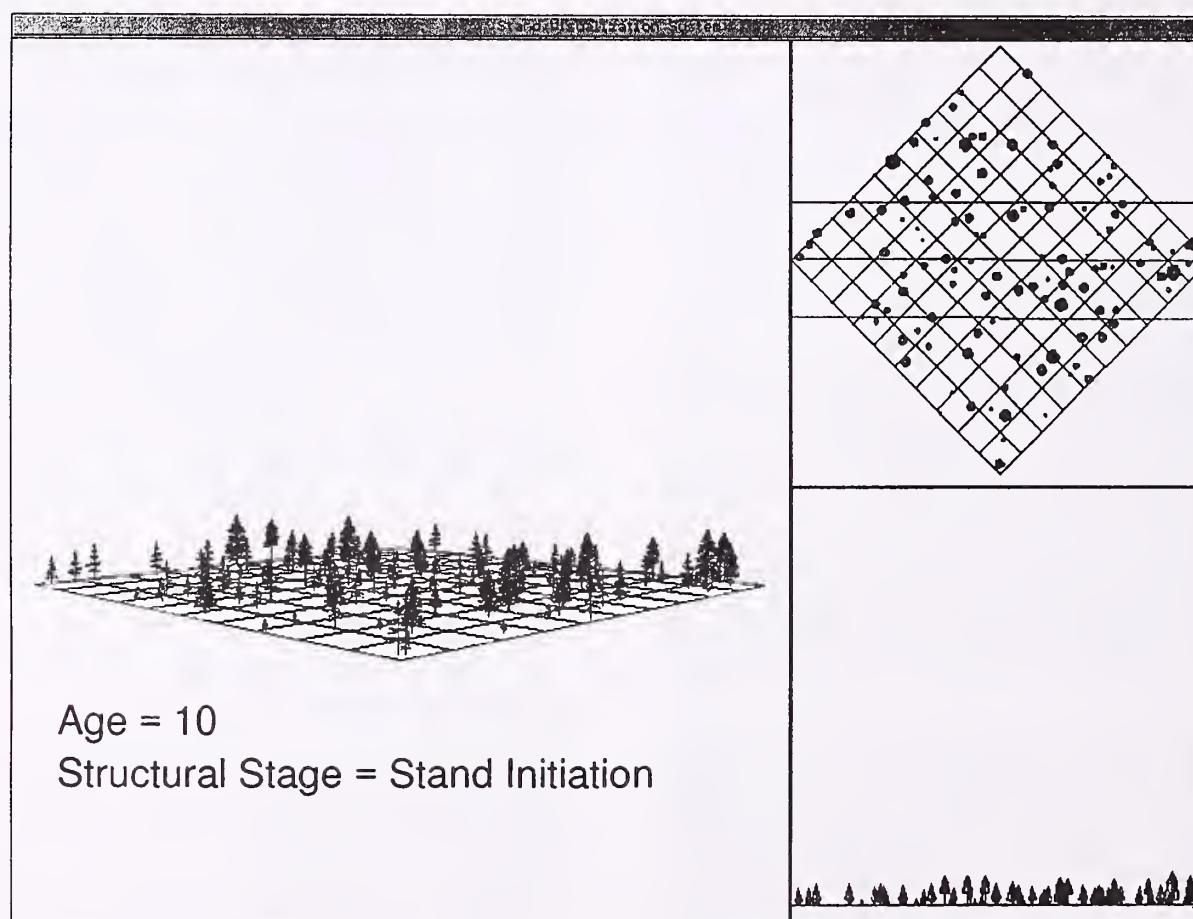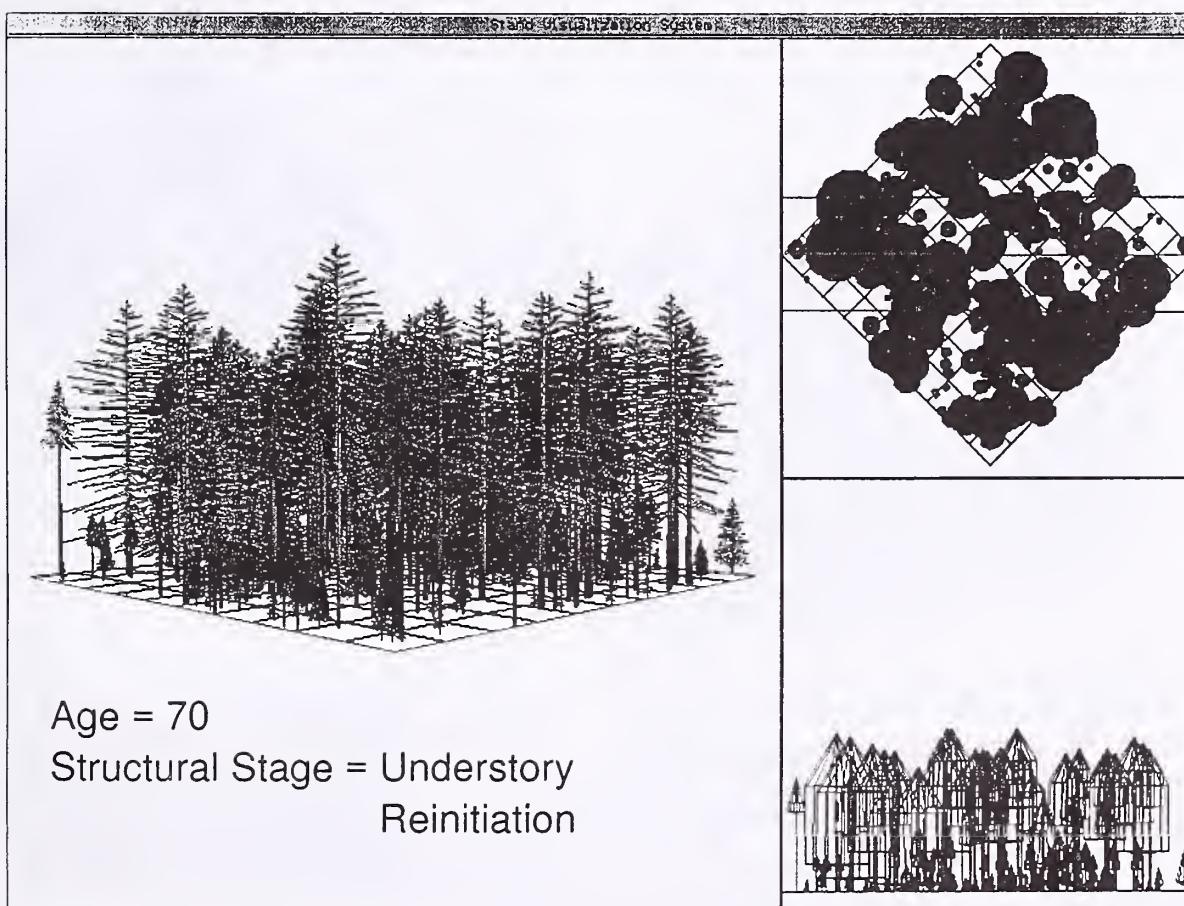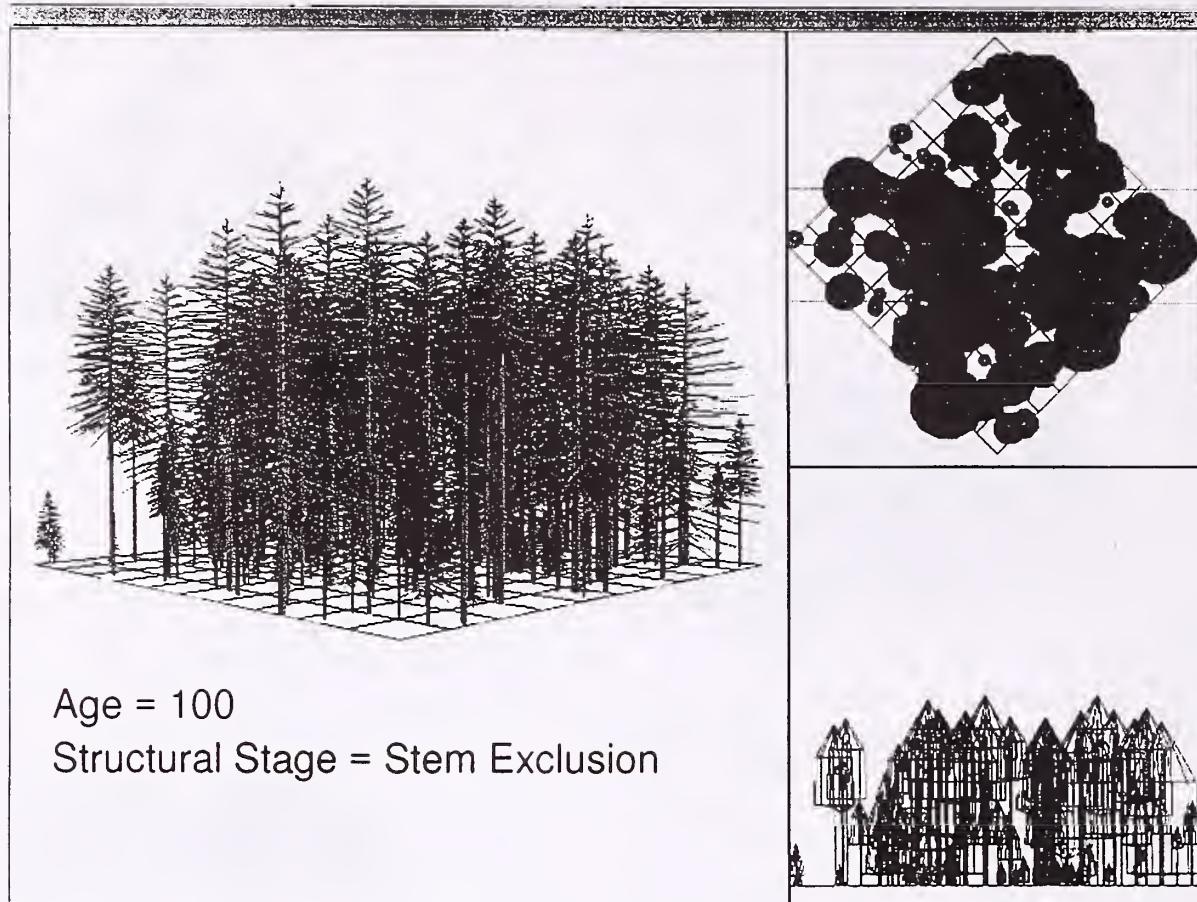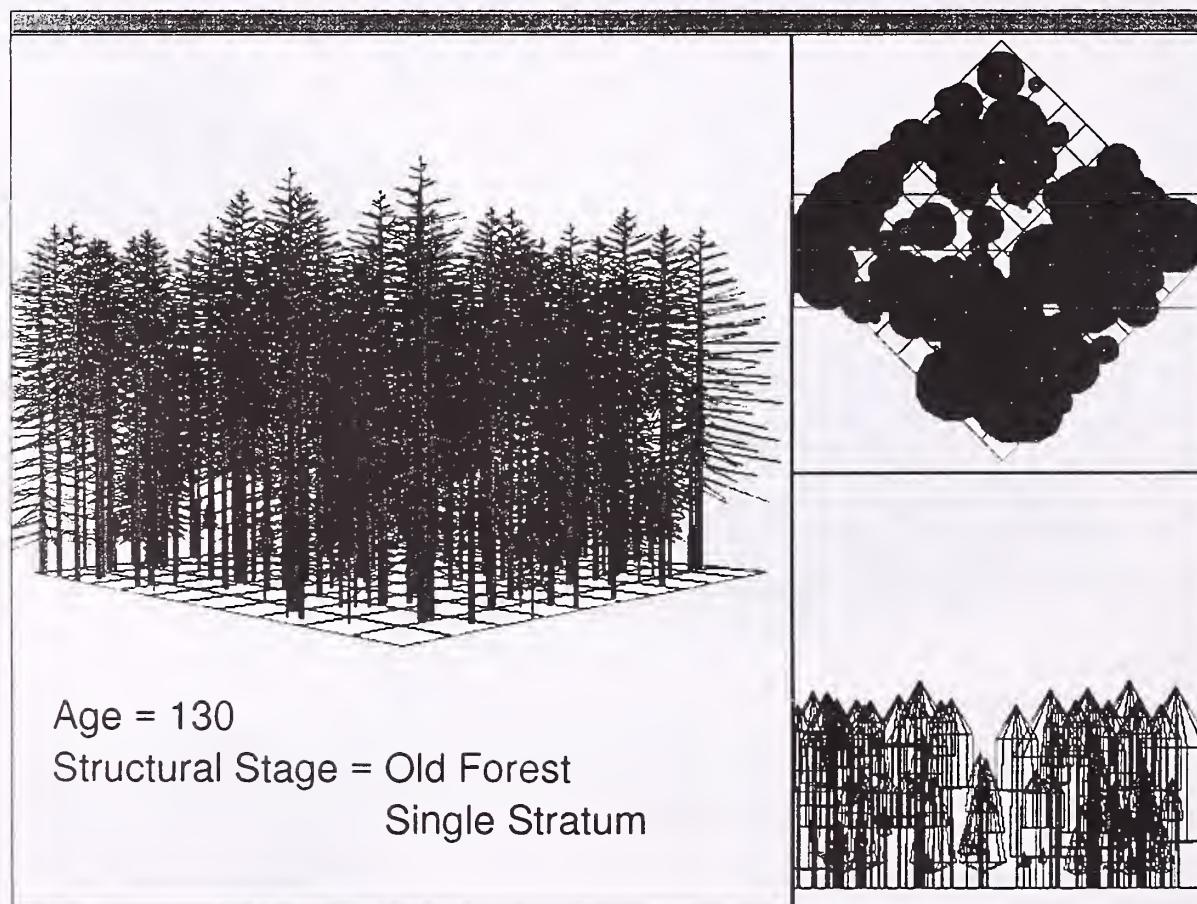
Figure 6—Example of Stem exclusion Structural Class based on classification of the Forest Vegetation Simulator tree list at 100 years.

Figure 7—Example of Old forest-Single stratum Structural Class based on classification of the Forest Vegetation Simulator tree list at 130 years.

is divided into (2) a thinning from below, (3) a shelterwood cut, and (4) a selective harvest spread across all size classes of trees. During each simulation run of CRBSUM, a random number generated from a uniform distribution was compared to the disturbance probability for each of the types of harvest of a given pixel. If the pixel is selected for harvest, it is reclassified according to the identified disturbance pathway.

CRBSUM was modified to record the years remaining before a pixel designated for harvest would move to the next successional class along the normal path. For each Structural Class/PVT combination, CRBSUM reports a frequency distribution of area cut for each type of harvest, with a further division by time remaining before the pixel would move to the next class. In a subsequent calculation, a volume-per-acre cut summarized from the FVS simulations was multiplied by the area cut in the CRBSUM simulation. This procedure is a simple refinement of the area disturbed by harvest that was already a planned report from CRBSUM.

The merit of this approach is that it relies on the future course of development of stands as simulated by FVS without relying on the effect of past stand development as embodied in successional age. The volume estimate is derived by a method that is logically independent of the analysis of residence time. It does not, therefore, require any assumptions that might contradict the logic behind the derivation of the parameters that are input to CRBSUM, and which ultimately define the model. It does, however, rely on the ability of the classification logic to properly label the structural classes. The responsibility for initiating a CRBSUM simulation with stands at appropriate successional ages within a class and for assigning an appropriate successional age following disturbances remains with those experts who define CRBSUM by providing the residence times and pathways.

For complete stand harvest, the volume that could be harvested by clear-felling is simply the estimated standing volume produced for a no-management scenario for the appropriate years remaining in the class. For partial harvests, multiple runs of the same stand invoked partial harvests scheduled at different times in the stand's development. FVS can, through use of the event monitor (Crookston 1990), schedule a simulation of a harvest when certain stand conditions are met. This capability permits the imposition of constraints on whether sufficient volume would be removed for an economically viable operation. For thinnings, the constraint on whether to thin or not can be made conditional on the density and species composition of the stand. These prescriptions can be made specific for the management scenario under which the product yield is to be calculated.

Source Data

Two FVS simulation methods were followed. One method for the Grand fir-Cedar-Hemlock classes of Potential Vegetation started each simulation from "bare ground" by using the Regeneration Establishment component of the Inland Empire variant of FVS to provide estimates of ingrowth. The model was run for the 158 stands representing the combinations of slope, aspect, elevation, and habitat type that were used in assembling the tables of stand development by site index and age (Stage and others 1988). The weights for these stands were proportional to the incidence of these classes in the forests of the Inland Empire as derived from the National Forest's inventories and from the Forest Inventory and Analysis Program inventories for the remaining forested area.

The second set of analyses used ground-based inventories supplied by the Forest Management Service Center in Fort Collins, CO. These stands were selected proportional to the area of forested lands in the Columbia Basin. A simulation of the development of each of these stands was analyzed by the same procedures outlined above. These analyses differed in that the initial successional ages of the stands could not be determined. Hence, the simulation could only define a minimum time to the first transition. Thereafter, the information was the same as was derived from the bare-ground analyses.

The Regeneration Model was invoked in the FVS system after silvicultural treatments (thinning or harvest) or by the Event Monitor whenever natural mortality caused the Crown Competition Factor (CCF) to fall below 85 and the mean d.b.h. of the stand was greater than 6 inches.

The broad-scale ICRB analyses had a resolution of 1 km^2 (247 acres) per pixel. The inventory data, on the other hand, were from clusters of five to 15 sample points per stand or location. At each sampling point, a combination of a small fixed-area plot and a variable-radius plot design with basal-area factors of about 20 ft^2 per acre were installed to produce a list of trees with their associated sampling probability and tree attributes. This disparity in the spatial extent of the analysis units must be considered when comparing the successional pathways in CRBSUM with those generated by FVS. Classes generated from FVS data will have larger sampling variability because the area within the sample is smaller. Therefore, the rare or unusual classes will occur more frequently in the FVS simulations than in CRBSUM.

Results

Succession Rates

Rates of stand development in the two systems are compared by plotting the successional age for each successional class in the pathway of CRBSUM over the age for the same structural class in the sequence generated by FVS. The ideal match would be for the line connecting the classes to lie along the 1:1 diagonal. The temporal sequences of structural classes for the Interior cedar/hemlock PVT (*Thuja/Tsuga*) are displayed in figure 8 for only cases where the two pathways follow the same sequence of structural classes. The match to the 1:1 line is reasonably good—an affirmation of the competence of the workshop participants. However, the somewhat flatter trends suggests that CRBSUM assumes that trees grow faster than FVS indicates. Of all the cover types, only the calibration of CRBSUM for *Pinus monticola* has the Old forest-Single stratum follow the Stem exclusion class. For all other cover types, CRBSUM has Understory reinitiation and Old forest-Multistrata follow Stem exclusion, whereas the simulations by FVS showed Old forest-Single stratum to follow Stem exclusion. The discrepancy may be the result of differences between how
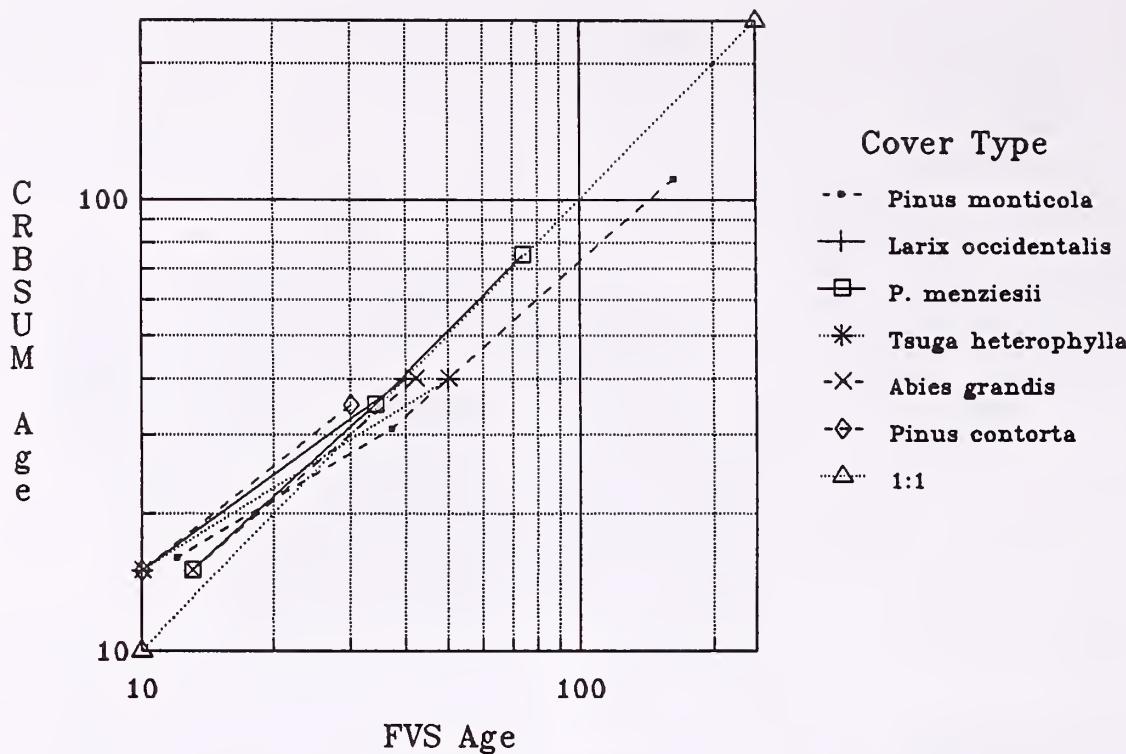
Figure 8—Comparison of rates of succession as modeled by CRBSUM and FVS for Cover Types of the Cedar/Hemlock Potential Vegetation Type. All pathways start with Stand initiation.

the developers of the concepts of structural classes and the teams of specialists who defined the CRBSUM pathways viewed disturbances.

Agents of mortality operating above some threshold are considered a "disturbance" and are modeled by a specific pathway. Mortality rates below this threshold are considered part of undisturbed succession. If the team calibrating CRBSUM sets this arbitrary threshold relatively high, the understory regeneration will become established and survive to produce the Understory reinitiation class. If, on the contrary, the threshold for disturbance is lower, the understory regeneration will either never enter, or will enter and be suppressed, as it did in the simulations leading from figure 5 to figure 6.

Harvest Volume

Harvest volumes for each of the four harvest types (clearcut, thinning, shelterwood, and partial cut) were averaged separately for each combination of time remaining to move to the next Structural Class and PVT, Cover Type, and the National Forest from which the inventory data had been obtained. This last level of delineation provided a crude means to localize the volume data for effects not related to PVT and Structural Class. In addition to measures of cubic volume, averages of basal area and numbers of stems also were computed so that the relative size of the trees harvested could be displayed.

The final step was to prepare summary software to extend the volume data for each geographic area. Although the inventory data were extensive, there were inevitable gaps when the areas harvested in the CRBSUM simulations were matched with the FVS-produced volume data. Therefore,

the summary software was programmed with substitution rules. Default data were sought first from nearby geographic areas, then from similar types of potential vegetation with adjustments for relative productivity.

As a final check on the calculation of volumes, the Forest Service contracted with ESSA Technologies, Ltd., to incorporate the volume calculations into the VDDT simulation package (Beukema and Kurz 1995b). With this tool, we can identify and evaluate possible inconsistencies in volume development that are the consequence of linking these two disparate modeling systems.

Discussion

There were two significant outcomes of this endeavor. First, we showed that it is possible to validate a model calibrated solely by expert opinion by building links to models with strong empirical bases. However, the linkage does not replace all subjective assumptions. Rather, it replaces the need for assumptions that can be verified only through long-term studies with assumptions that can be verified by one-time observations. The simulations would have been more useful if field tests had verified the parameters of the classification rules before they were used. At least the developers of the Structural Classes could review the behavior of the rules by examining the Stand Visualization System representations of sample stands as they developed during the course of the simulations. Unfortunately, this study will not commence before the ICRB analyses are completed.

Second, we demonstrated that providing a subjective successional pathways model with objective estimates of stand attributes, such as standing biomass and harvest

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volumes, is possible without the need for field sampling. This portion of the analysis could have been improved if the field samples to initiate the FVS simulations had been obtained through rigorous sampling procedures.

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Appendix: Retrogression Algorithm

Steps to avoid illogical transitions:

1. Place a marker in each cell of the "From/To" transition matrix that signifies retrogression (information obtained from the successional pathway diagrams).

2. For each developmental sequence, classify the tree list into the corresponding sequence of classes.

3. Scan the class sequence for transitions.

4. If the transition is not retrogressive, then enter data for residence time. Otherwise, compare the mean diameter of trees in the dominant stratum of the source class to the upper boundary of the receiving class. If the difference is less than one-sixth of the interval spanned by the definition of the receiving class, then change the receiving class to equal the source class (that is, erase the retrogression).

Note: Decreases in mean diameter that cause retrogression may be a consequence of new regeneration entering the tree list. The above algorithm, in effect, decreases the boundary diameter of the more advanced class, so that the stand does not leave the more advanced successional class so quickly.

Simulating Catastrophic Disturbance Effects on Coarse Woody Debris Production and Delivery

Don C. Bragg

Abstract—For decades, coarse woody debris (CWD) recruitment has remained a largely unknown component of riparian zone management. The integration of the Forest Vegetation Simulator (FVS) and a mechanistic CWD recruitment post-processor (*CWD*) provided insights into some of the factors involved in CWD delivery through the comparison of two simulated catastrophic disturbances (a spruce beetle outbreak and a clearcut) and an unmanipulated old-growth control. Compared to the old-growth control, spruce beetle-impacted riparian forests varied the timing and increased the overall delivery of CWD, while the clearcut reduced delivery and in-stream loads for many years. This exercise also suggested that natural catastrophic disturbance in riparian forests may bolster CWD recruitment, a process that could prove beneficial in the recovery of CWD-depauperate streams.

Coarse woody debris (CWD—pieces of wood at least 1 m in length and 10 cm in diameter) has been recognized as a critical component of many ecosystems (Bisson and others 1987; Harmon and others 1986; Maser and Trappe 1984; Triska and Cromack 1980). This is especially true for riparian zones since CWD contributes much of the structure, habitat, and storage capacity of streams (Bilby 1984; Harmon and others 1986; House and Boehne 1987; Ralph and others 1994). However, even though this factor is important in determining stream health, little is known about the processes involved in riparian CWD recruitment. Prior research has focused on CWD source distances (McDade and others 1990; Murphy and Koski 1989; Rainville and others 1985), direction of tree fall (Rainville and others 1985; Robison and Beschta 1990; Van Sickle and Gregory 1990), and in-stream CWD dynamics (Bilby and Ward 1989; Lienkaemper and Swanson 1987; Murphy and Koski 1989). Yet, due to the lack of information, these (and other) efforts make a number of assumptions about CWD dynamics that may not hold ecologically. For example, virtually all studies on riparian CWD delivery focus on small-scale (individualistic) recruitment in which single trees die, fall in a random pattern, and potentially enter the stream. No attempts to quantify the contribution of large-scale (catastrophic) recruitment or the differences between catastrophic disturbances have been made. In this paper I address the differential impacts of individualistic and catastrophic riparian CWD recruitment, and contrast two different catastrophic disturbances of Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) dominated old-growth riparian forests in northwestern Wyoming using the Teton Variant (v6.1) of the Forest Vegetation Simulator (Wykoff and others 1982) and a riparian CWD recruitment post-processor (*CWD*).

Methods

Study Area Description

The stream selected for these simulations, Dry Lake Creek, is located northeast of Jackson, WY, in the Bridger-Teton National Forest. A second-order stream flowing through unmanaged spruce-fir old-growth in its upper reaches, the 250 m sample reach had a mean bankfull width of 5.5 m, an average gradient of 3.5 percent, sinuosity <1.1, an average elevation of 2,565 m, and drained a basin of approximately 1,030 ha (Bragg and others, in preparation). All scenarios used stream and riparian forest inventory data from a 1995 survey of this reach (Bragg and others, in preparation).

Model Development

In order to quantify long-term riparian CWD recruitment, patterning both forest dynamics and delivery mechanisms was vital. These functions were provided by linking *CWD* and FVS. Interestingly, the integration of *CWD* and FVS revealed unanticipated difficulties. The standard growth rates of FVS overestimated yield and underestimated mortality for spruce-fir forests in northwestern Wyoming. The paucity of large CWD recruited to the stream during preliminary runs suggested that the big trees critical for riparian CWD weren't being accumulated in the mortality queues. This problem was corrected by adding mortality above FVS defaults in the largest size classes via modifying keywords (in this case, FIXMORT). Another problem that arose because of the long simulation period was the need to realistically regenerate the simulated stand. This was achieved with the Event Monitor (see Crookston and Ferguson 1990; Ferguson and Carlson 1993), and matched to previously reported spruce-fir regeneration surveys.

Riparian forest regeneration, growth, and individualistic mortality were simulated using modified keyword files to adjust FVS defaults (appendix). Catastrophic disturbance was implemented by FVS with the FIXMORT keyword for the natural catastrophe and the THINDBH keyword to generate the management scenario (appendix). Other riparian CWD recruitment processes were controlled by the *CWD*

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post-processor. *CWD* read the tree list output file generated by FVS, determined mortality by tree record, and then extracted the relevant dimensional data. Once *CWD* acquired this tree information, it randomly located stems throughout a user-defined riparian forest buffer, calculated snag residency (as a function of time since death, diameter, and species), determined angle of snag fall, and selected the pieces of CWD delivered to the stream. There are no further spatial components to CWD recruitment in the post-processor beyond the random distance-to-stream assignment, nor are there components of stream channel behavior in the current version of *CWD*. Stochasticity was introduced into the simulation through each of the 20 replicates performed via randomization factors imbedded in snag location, angle of fall, and fragmentation routines. *CWD* calculated delivery in terms of volume per reach (m^3 per 100 m reach), while instream CWD dynamics followed assumptions of Bragg and Kershner (1997) for steady-state load dynamics.

Ecological Comparisons of Disturbance

For simulation purposes, catastrophic disturbances were severe, large-scale perturbations that devastated the original riparian forest (that is, stand-replacing events). All catastrophes were initiated only once (in year 50) during the 300 yr simulation period. Individualistic disturbance, on the other hand, represented the small-scale, density-dependent mortality provided by FVS. Rather than being temporally discrete, individualistic disturbances occurred continually in all scenarios.

The natural catastrophic disturbance treatment involved a severe spruce beetle (*Dendroctonus rufipennis* [Kirby]) outbreak in which 95 percent of the Engelmann spruce >10 cm d.b.h., 50 percent of Engelmann spruce <10 cm d.b.h., and 50 percent of lodgepole pine >10 cm d.b.h. were killed in year 50. This ratio of mortality followed severe outbreak patterns observed for spruce beetle (Baker and Veblen 1990; Holsten and others 1991; Schmid and Hinds 1974; Veblen and others 1991) in which some small Engelmann spruce, most lodgepole pine, and virtually all subalpine fir escaped outbreak-related mortality. The clearcutting scenario harvested 95 percent of the overstory >10 cm d.b.h. regardless of species, thereby removing the vast majority of the original riparian stand. The THINDBH keyword generated very substantial differences between these catastrophes because it 'exported' the mortality, whereas the trees killed by the simulated spruce beetle outbreak remained on the site as snags. Catastrophic disturbances therefore not only differed substantially from the individualistic-only scenario, but also amongst themselves.

Results and Discussion

Figure 1 shows the impacts of each scenario on the riparian forest. The no-treatment (individualistic recruitment only) riparian forest was held at approximately $40 \, m^2 \, ha^{-1}$ of basal area during the simulation via a combination of regeneration and mortality initiated by the keyword file (appendix). All scenarios followed the same density trajectory until catastrophic disturbances were induced in year 50. After event initiation, the spruce beetle treatment dropped to
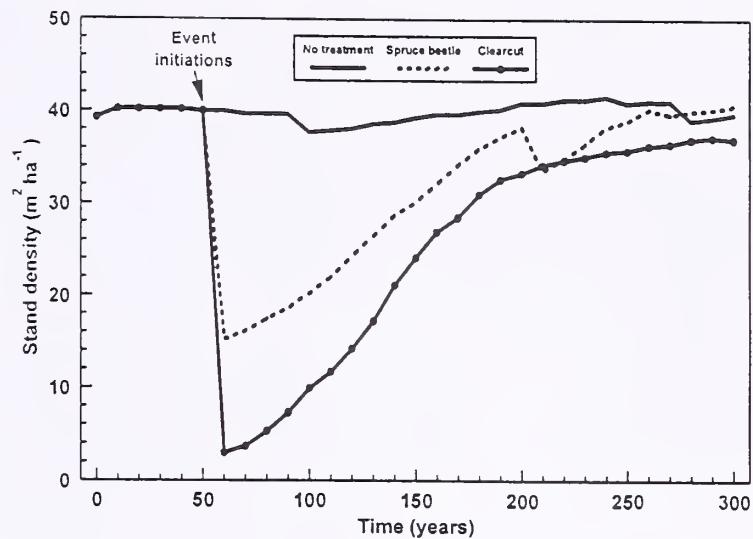
Figure 1—Projected stand density (in $m^2 \, ha^{-1}$) under individualistic (no treatment, solid line), spruce beetle (dashed line), and clearcut (dotted line) scenarios. Treatment trajectories result from differential disturbance impacts on the riparian stand, variability in stand recovery, and FVS and *CWD* model effects.

about $\frac{1}{3}$ the original undisturbed stand density even though the decline was mediated by the subalpine fir and lodgepole pine survivors. The clearcut treatment, however, reduced riparian stand density to one-tenth initial levels as harvest mortality was more intensive and less selective than the spruce beetle. Eventually, both catastrophes recovered to approximately pre-disturbance levels 150 to 200 yr after perturbation. Differences in recovery initiation and trajectory were deliberately unique to reflect the variable nature of catastrophic disturbance impacts.

The no-treatment scenario was predicted to deliver about 2 to 4 m^3 of CWD per 100 m reach per cycle (fig. 2). Consistent delivery was expected for undisturbed old-growth stands that fluctuate little in structure or density through time (as controlled in this project). However, the spruce beetle-impacted scenario experienced a large spike of riparian CWD recruitment (up to 12 $m^3 \, 100 \, m^{-1}$ reach) immediately after the catastrophe that continued for a half-century after the outbreak. This peak arose as a large number of new snags created by the outbreak lost their structural integrity and fell into Dry Lake Creek. The volume of CWD delivered rapidly declined 40 to 50 yr after the event, and fell below the expected no-treatment levels for several cycles. As recruitable snags became less frequent, the recovering riparian forest became the primary source of CWD. Since recovering stands tend to be more vigorous and contain smaller individuals, volumetric recruitment lessened briefly following catastrophic disturbance when compared to the expectations from undisturbed old-growth (fig. 2) (see also Murphy and Koski 1989). Gradually, the spruce beetle-impacted riparian forest recovered sufficiently to match delivery from the individualistic only scenario.

Clearcutting yielded a considerably different riparian CWD delivery pattern than either no-treatment or spruce beetle-affected stands (fig. 3). Rather than experiencing a large spike in CWD recruitment, delivery dropped to zero
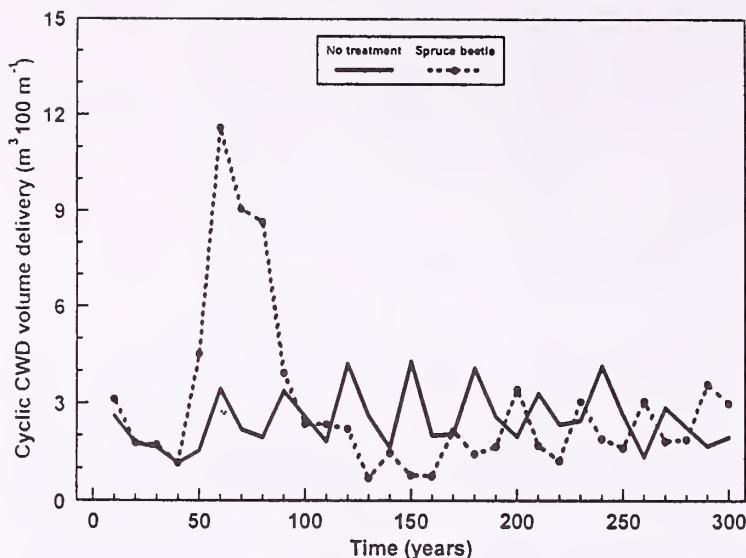
Figure 2—Cyclic CWD delivery rates for the no catastrophic disturbance treatment and a simulated spruce beetle outbreak (event in year 50). The large spike of recruitment developed after snags created by the outbreak began falling into Dry Lake Creek and elevated delivery is maintained for several decades during the stand's recovery because of individualistic mortality in the residual subalpine fir. All projections represent the average of 20 replicates.
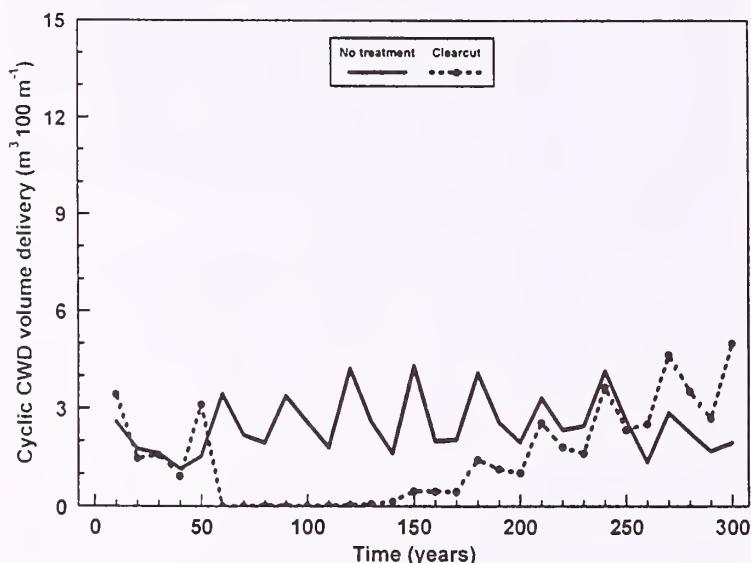
Figure 3—Cyclic CWD delivery rates for the no catastrophic disturbance treatment and a simulated clearcut (event in year 50). Unlike the spruce beetle scenario, no concurrent peak of CWD recruitment followed the clearcut because of the absence of biomass to recruit from.

and stayed negligible for many decades as the ultimate source of CWD (the riparian forest) had been virtually eliminated (similar to predictions of Murphy and Koski [1989] for some Alaskan streams). Since there are very few snags to contribute after this catastrophe, delivery was inconsequential until more than a century after the event. As with the spruce beetle scenario, recruitment eventually

returned to pre-disturbance levels, but the sustained lack of delivery has serious implications for long-term riparian CWD stocks.

Figure 4 compares the relative cumulative impacts of the simulated disturbances. The individualistic-only treatment gradually added CWD throughout the simulation, approaching 75 m^3 100 m^{-1} reach. Under the spruce beetle scenario, cumulative delivery rapidly grew in the first few decades after the disturbance before moderating at a rate of accumulation similar to the no-treatment scenario. However, this natural catastrophe was predicted to deliver significantly higher cumulative volume than under individualistic-only recruitment by the end of the simulation period (about 88 m^3 100 m^{-1} reach), probably because many long-lived Engelmann spruce were killed prematurely by the spruce beetle outbreak and converted rapidly into riparian CWD. Further simulations have also indicated that other types of catastrophic disturbance also result in increased cumulative CWD recruitment (D. C. Bragg, unpublished data). This suggests that following natural catastrophic disturbance in riparian forests, long-term recruitment may inflate above what would be expected in undisturbed old-growth, and could therefore prove an important tool in recovering streams lacking appreciable CWD loads. The clearcut scenario, however, experienced many decades of little to no recruitment and failed to recover the no-treatment levels during the 300 yr simulation period, delivering less (only 46 m^3 100 m^{-1}) than the other treatments (fig. 3, 4). All final cumulative delivery volumes differed significantly from each other (α = 0.05, Tukey's multiple comparison test).

Converting these periodic delivery measures to tangible riparian CWD loads required addressing in-stream CWD attrition. Following earlier efforts (for example, Bragg and Kershner 1997), I assumed that the stream was capable of
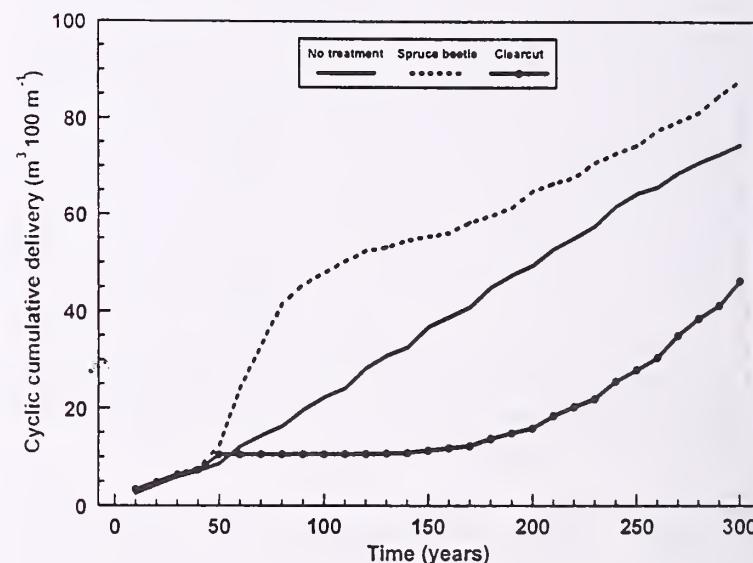
Figure 4—Cumulative recruitment (m^3 100 m^{-1} reach) over the simulation period. All treatments were significantly different in total delivery for most of the simulation period after the catastrophes were initiated in year 50 (α = 0.05, Tukey's multiple comparison test). Notice how spruce beetle outbreak has increased cumulative recruitment over the no-treatment (individualistic-only) scenario.

moving a fixed percentage of its riparian CWD load every cycle (derived from field CWD inventories and predicted individualistic recruitment rates), thereby approximating how much of the predicted delivery was retained through time as a measure of in-stream CWD load (fig. 5). The turnover rate applied in this effort (28.8 percent per cycle, or 2.88 percent annually) is similar to other reports (for example, Bilby and Ward 1991; Maser and Sedell 1994; Murphy and Koski 1989) and probably reasonably matches actual attenuation in Dry Lake Creek. Once again, because of its consistent level of riparian CWD delivery, the no-treatment scenario in-stream CWD loads fluctuated very little over time. This 'steady-state' load varied from 8 to 10 m^3 100 m^{-1} reach (close to the 1995 Dry Lake Creek inventory of 8.6 m^3 100 m^{-1}).

Following a simulated spruce beetle outbreak, however, Dry Lake Creek experienced a large increase in CWD load (up to 24 m^3 100 m^{-1} reach) that peaked 3 decades after the event. This lag resulted from the sustained influx of snags that exceeded the stream's capacity to attenuate the newly delivered CWD. Eventually, snag recruitment failed to keep up with the volume of material flushed out of the stream, and in-stream CWD loads dropped until, approximately a century after the disturbance, they fell below the levels expected under a no-treatment scenario. Post-beetle riparian forests had not recovered sufficiently at this stage to compensate for the loss of delivery, resulting in a decrease from no-treatment loads for almost a century. Eventually, regrowth and CWD delivery matched that under the no-treatment scenario. However, as is apparent in figure 5, the oscillation of in-stream CWD load induced by even a single catastrophic disturbance questions the validity of assuming long-term or steady-state riparian CWD loads.

Clearcutting, as expected, did not experience an in-stream CWD peak after disturbance, but rather a sharp and steady decline for decades (fig. 5). Depending on the intensity of the disturbance, the loss of CWD delivery coupled with constant in-stream CWD attrition could drive the riparian CWD load to virtually nothing. Earlier research (for example, Bragg and Kershner 1997) had suggested that timber harvest and riparian cleaning might eradicate riparian CWD, but this simulation indicated that CWD may be temporarily eliminated even without active extraction if the treatment is severe enough. Other field studies have considered the effects of riparian forest harvest with mixed results. After analyzing numerous western Washington stream systems decades after harvest, Ralph and others (1994) concluded that intensely harvested drainages had similar piece frequencies but lower volumes than moderately cut or unharvested watersheds. However, Carlson and others (1990), in a similar study of harvested and undisturbed drainages in the Pacific Northwest found no differences in riparian CWD characteristics, regardless of treatment. It is possible that Carlson and others' (1990) watersheds have not "advanced" sufficiently to show long-term impacts, but Bilby and Ward (1991) have indicated most CWD depletion occurred during the first decade after harvest. Andrus and others (1988) documented low riparian CWD recruitment 50 yr after clearcutting and fire in small riparian systems with no buffer strips. Murphy and Koski (1989) modeled clearcutting Alaskan riparian stands with no buffers and predicted that 90 yr after treatment, large CWD would decline by 70 percent and recovery to pre-logging loads would take 250 yr. While this study forecasts more rapid CWD recovery (probably due to faster stand regrowth), it fits well with Murphy and Koski's (1989) predictions and parallels the empirical trends noted by others (for example, Andrus and others 1988; Bilby and Ward 1991). Sustaining riparian CWD recruitment, especially of larger pieces, is paramount to supporting healthy stream structure (Andrus and others 1988; Carlson and others 1990; Murphy and Koski 1989; Ralph and others 1994).

Conclusions

In times of declining research budgets and increased demand on our natural resources, we are dually challenged by the need for better management. Operations that apply existing technology with new approaches can provide some answers at low cost. The coupling of a commonly applied growth and yield model (FVS) with a mechanistic post-processor (*CWD*) has provided insight into the dynamics involved in riparian CWD recruitment. Substantial differences exist in the recruitment patterns initiated by catastrophic and individualistic recruitment, both in the timing and the volume of the delivery. This variance was especially pronounced between natural and anthropogenic events, but also probably differs between natural catastrophes. Systems affected rarely (every few hundred years) by catastrophic disturbance develop long-lasting changes in riparian CWD via the alteration of loading patterns and cumulative delivery.
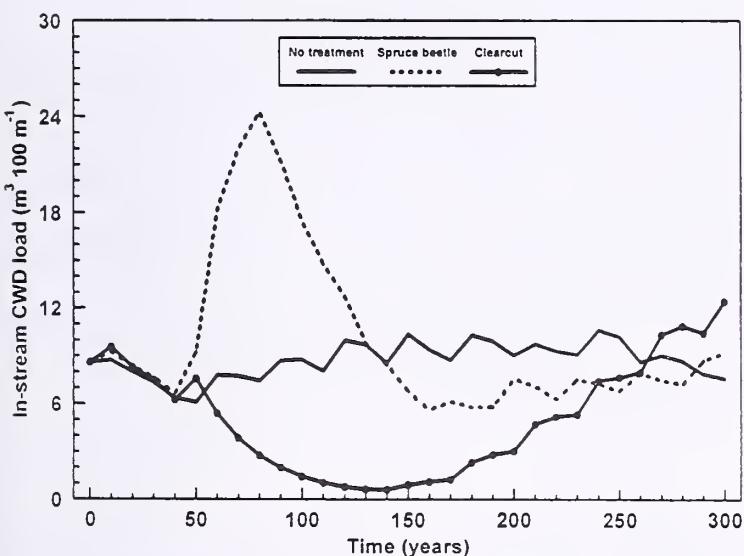
Figure 5—In-stream CWD loads as a function of treatment during the simulation period. The no-treatment scenario approximated a steady-state load. Peak loads for the spruce beetle outbreak came about 30 yr after the catastrophe occurred, resulting from steady snag input and insufficient attrition of CWD by Dry Lake Creek. Clearcutting caused an immediate and prolonged decrease in in-stream CWD load, severely affecting CWD-related stream processes.

Acknowledgments

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Appendix: FVS Keyword Files Used to Generate Disturbance Scenarios

No-treatment scenario keyword file

```
SCREEN
STATS
* THIS KEYWORD FILE IS DESIGNED FOR AN OLD-GROWTH STAND-  DRY LAKE CREEK
STDIDENT
TETON#03
DESIGN            -5.0         5         999         4
*                 Field1    Field2      Field3    Field4      Field5      Field6
INVYEAR           1995.0
NUMCYCLE            31.0
ESTAB             2000.0
NATURAL           2003.0       7.0       10.0        10.0
NATURAL           2003.0       8.0      600.0        20.0
NATURAL           2003.0       9.0     1000.0        30.0
END
FIXMORT              0                   .030        35.0      999.0           1
FIXMORT              0                   .045        25.0       34.99          1
FIXMORT              0                   .060        15.0       24.99          1
FIXMORT              0                   .075         7.5       14.99          1
FIXMORT              0                   .090         0.0        7.49          1
IF
BBA GT 125 AND BBA LE 200
THEN
ESTAB                2.0
NATURAL              0.0       8.0       50.0        55.0
NATURAL              0.0       9.0      100.0        60.0
END
ENDIF
IF
BBA GT 75 AND BBA LE 125
THEN
ESTAB                2.0
NATURAL              0.0       8.0      100.0        30.0
NATURAL              0.0       9.0      200.0        35.0
END
ENDIF
IF
BBA GT 25 AND BBA LE 75
THEN
ESTAB                2.0
NATURAL              0.0       7.0       20.0        10.0
NATURAL              0.0       8.0      200.0        20.0
NATURAL              0.0       9.0      400.0        30.0
END
ENDIF
IF
BBA LE 25
THEN
ESTAB                2.0
NATURAL              0.0       7.0     1000.0        10.0
NATURAL              0.0       8.0     1500.0        15.0
NATURAL              0.0       9.0     2000.0        20.0
END
ENDIF
STDINFO            415                  300.0          0        5.0        83.0
43.0
TREELIST             0                   -1                     1
NOTRIPLE
TREEDATA
ECHOSUM
PROCESS
STOP
```

Spruce beetle scenario keyword file

```
SCREEN
STATS
*   THIS KEYWORD FILE IS DESIGNED FOR AN INSECT DAMAGED STAND-    DRY LAKE CREEK
STDIDENT
TETON#03
DESIGN           -5.0         5        999          4
*               Field1      Field2    Field3     Field4      Field5      Field6
INVYEAR         1995.0
NUMCYCLE          31.0
ESTAB           2000.0
NATURAL         2003.0        7.0      10.0       10.0
NATURAL         2003.0        8.0     600.0       20.0
NATURAL         2003.0        9.0    1000.0       30.0
END
FIXMORT              0                 .030       35.0       999.0          1
FIXMORT              0                 .045       25.0       34.99          1
FIXMORT              0                 .060       15.0       24.99          1
FIXMORT              0                 .075        7.5       14.99          1
FIXMORT              0                 .090        0.0        7.49          1
FIXMORT         2046.0        7.0      .500        4.0       999.0          0
FIXMORT         2046.0        8.0      .950        4.0       999.0          0
FIXMORT         2046.0        8.0      .500        0.0        3.99          0
IF
BBA GT 125 AND BBA LE 200
THEN
ESTAB              2.0
NATURAL            0.0         8.0      50.0       55.0
NATURAL            0.0         9.0     100.0       60.0
END
ENDIF
IF
BBA GT 75 AND BBA LE 125
THEN
ESTAB              2.0
NATURAL            0.0         8.0     100.0       30.0
NATURAL            0.0         9.0     200.0       35.0
END
ENDIF
IF
BBA GT 25 AND BBA LE 75
THEN
ESTAB              2.0
NATURAL            0.0         7.0      20.0       10.0
NATURAL            0.0         8.0     150.0       20.0
NATURAL            0.0         9.0     400.0       30.0
END
ENDIF
IF
BBA LE 25
THEN
ESTAB              2.0
NATURAL            0.0         7.0     500.0       10.0
NATURAL            0.0         8.0    1000.0       15.0
NATURAL            0.0         9.0    2500.0       20.0
END
ENDIF
STDINFO            415                300.0          0        5.0        83.0
43.0
TREELIST             0                 -1                     1
NOTRIPLE
TREEDATA
ECHOSUM
PROCESS
STOP
```

Clearcut scenario keyword file

```
SCREEN
STATS
*   THIS KEYWORD FILE IS DESIGNED FOR A CLEARCUT STAND-   DRY LAKE CREEK
STDIDENT
TETON#03
DESIGN          -5.0          5         999           4
*              Field1      Field2      Field3      Field4      Field5      Field6
INVYEAR        1995.0
NUMCYCLE         31.0
ESTAB          2000.0
NATURAL        2003.0        7.0        10.0        10.0
NATURAL        2003.0        8.0       600.0        20.0
NATURAL        2003.0        9.0      1000.0        30.0
END
FIXMORT              0                   .030        35.0       999.0           1
FIXMORT              0                   .045        25.0       34.99           1
FIXMORT              0                   .060        15.0       24.99           1
FIXMORT              0                   .075         7.5       14.99           1
FIXMORT              0                   .090         0.0        7.49           1
THINDBH        2045.0        4.0         999         0.95
THINDBH        2045.0        0.5         4.0         0.50
IF
YEAR GT 2045
THEN
FIXMORT              0                   .010        35.0       999.0           1
FIXMORT              0                   .020        25.0       34.99           1
FIXMORT              0                   .030        15.0       24.99           1
FIXMORT              0                   .040         7.5       14.99           1
FIXMORT              0                   .050         0.0        7.49           1
ENDIF
IF
BBA GT 125 AND BBA LE 200
THEN
ESTAB             2.0
NATURAL           0.0        8.0        50.0        55.0
NATURAL           0.0        9.0       100.0        60.0
END
ENDIF
IF
BBA GT 75 AND BBA LE 125
THEN
ESTAB             2.0
NATURAL           0.0        8.0       100.0        30.0
NATURAL           0.0        9.0       200.0        35.0
END
ENDIF
IF
BBA GT 25 AND BBA LE 75
THEN
ESTAB             2.0
NATURAL           0.0        7.0        20.0        10.0
NATURAL           0.0        8.0       200.0        20.0
NATURAL           0.0        9.0       400.0        30.0
END
ENDIF
IF
BBA LE 25
THEN
ESTAB             2.0
NATURAL           0.0        7.0      1000.0        10.0
NATURAL           0.0        8.0      1500.0        15.0
NATURAL           0.0        9.0      2000.0        20.0
END
```

```
ENDIF
STDINFO        415              300.0        0        5.0       83.0
43.0
TREELIST         0               -1                   1
NOTRIPLE
TREEDATA
ECHOSUM
PROCESS
STOP
```
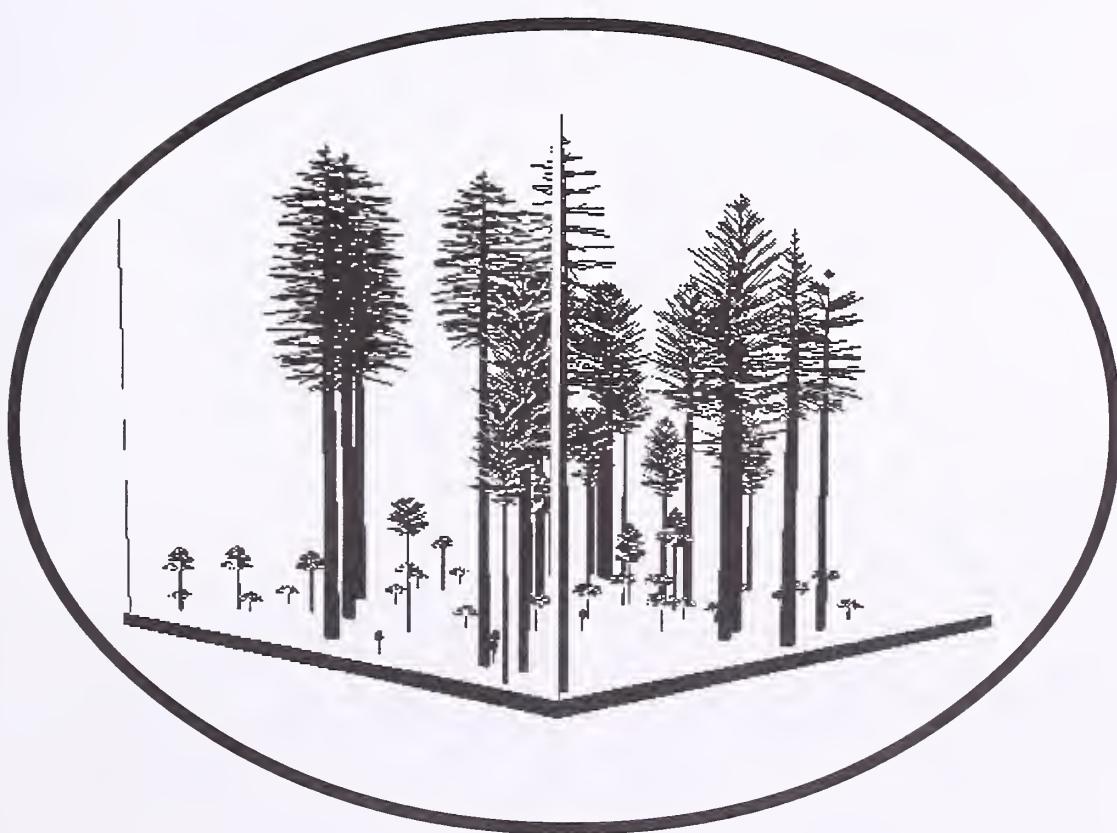
Visualization and New Model Extensions

Integrating Forest Inventory, Growth and Yield, and Computer Visualization into a Landscape Management System

James B. McCarter

Abstract—The Landscape Management System (LMS) is an evolving Microsoft Windows™ application that integrates forest inventory information, spatial information, growth models, computer visualization software, and analysis software into a landscape-level analysis tool. This paper presents an overview of the system, system objectives, system outputs, and examples of analyses that can be performed using the system.

A system designed to support landscape-level decision-making should provide estimates of future stand and landscape conditions. In order for the system to be extensively used, it must be widely available and be applicable across a range of geographic regions. Designing a system with broad geographical applicability requires either the use of a general growth model or the inclusion of many growth models to represent the different geographic areas. The use of models that represent different geographic areas should provide for better growth estimates because of a better relationship to the modeling database used to construct the growth model. Such a system can be made widely available by developing it for a popular computer operating system.

This paper presents an overview of the Landscape Management System (LMS), a Microsoft Windows program that integrates forest inventory information, spatial information, growth models, computer visualization, and analysis software into a landscape-level analysis tool. The first three sections describe system objectives, design, and available outputs. The final section presents example analyses performed on system output.

System Objectives

The primary objective of LMS is to provide a tool with which users can easily investigate landscape-level management options and compare the consequences of alternative management scenarios. Early in the design of LMS, it became clear that there was considerable software available that performed parts of the desired functionality of our

system. Rather than develop all new software that would duplicate what already existed, LMS was designed to integrate existing software and technologies where possible.

In order for LMS to have value beyond a specific analysis or geographical area, it needed to have flexibility and adaptability. A modular conceptual design allows for this flexibility and adaptability. New models and analysis tools can be incorporated into the system simply by developing the interface components and the configuration elements that tell the system how to operate the tool. Another way the system retains flexibility is by facilitating the transfer of inventory information (initial and projected) to other software for further analysis. This can be termed "down stream analysis." These analyses can be as simple as calculating stand level statistics or much more complicated, requiring multiple sources of information.

Microsoft Windows was selected as the LMS development environment for five reasons: (1) An evaluation of existing individual tree growth models and visualization tools indicated that the large majority were available for, or constrained to, the Microsoft MS-DOS operating system. Windows can run most MS-DOS applications. (2) The availability of good software development tools. (3) A large potential user base. (4) Windows allows for the development of a user interface that is easier to use and learn than a text based system. (5) Memory limitations in MS-DOS programming.

System Overview

The Landscape Management System (LMS) is an application that coordinates the flow of information between growth and yield models, computer visualization software, and analyses tools. LMS manages the activities of these various component programs along with the myriad of files used to communicate between the programs. This section describes the system.

Coordinating Application

The LMS interface (fig. 1) is implemented as a Microsoft Windows application that is operated by a series of menus and shortcut buttons. Information in LMS is contained in a number of related files that represent a land area. These files, along with any projections and treatments, are collectively called a portfolio. A portfolio includes all of the inventory and spatial files necessary for LMS to project and visualize stands and landscapes. Information about the current portfolio is displayed in the main LMS window (fig. 1).
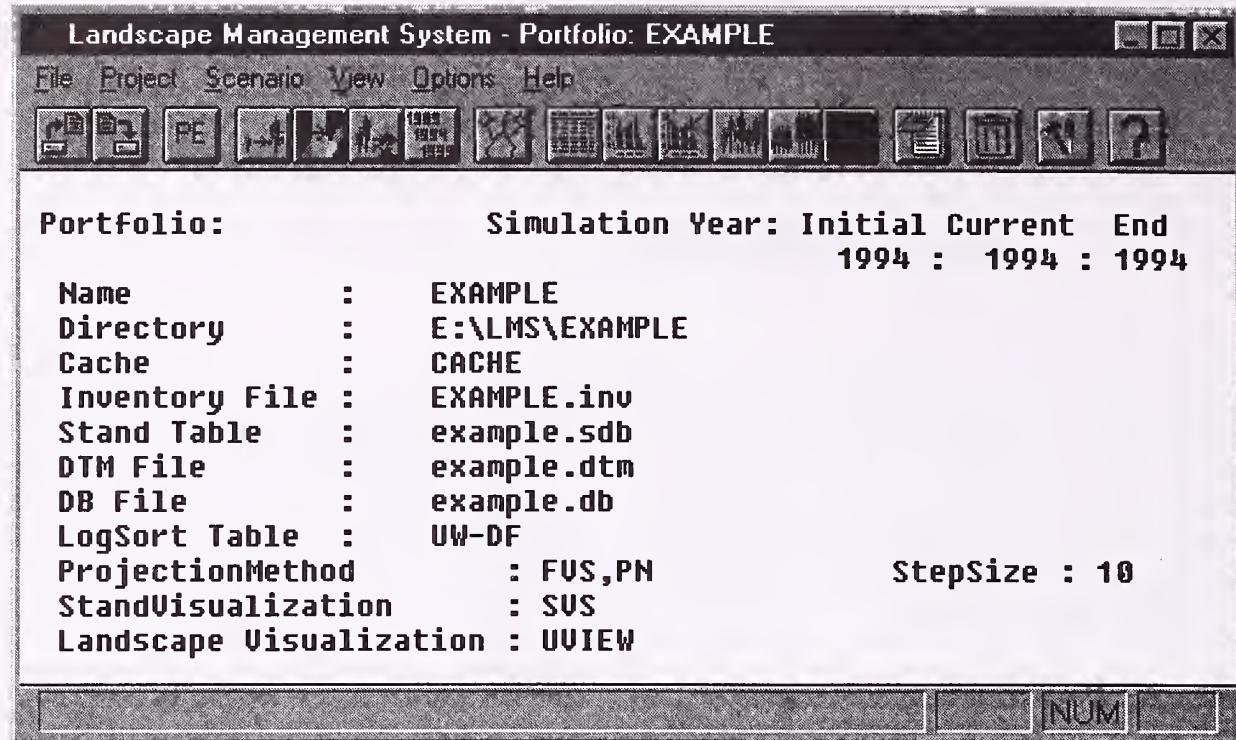
Figure 1—Main windows of LMS application.

Inventory Information

Initial Inventory—Inventory information in LMS includes record number, species code, diameter at breast height, tree height, crown ratio, expansion factor, and volume. This information usually comes from inventory plots. Either fixed area or variable plot cruises can be used. The results of inventory sampling must then be summarized into per acre values for use by LMS. For fixed area plots this consists of adding expansion factors to convert fixed area plots to represent a full acre (in other words, 1/10 acre plots would result in expansion factors of 10 for all trees measured in the plot). Variable plot cruise information is converted to per acre by using an appropriate expansion factor.

The inventory information used by LMS consists of an inventory for each stand that contains information about individual trees in the stand. The inventory is based on the individual trees measured on sample plots for the stand. Every measured tree is included in the individual tree inventory. An expansion factor represents the number of individuals each tree record represents on a per area (acre or hectare) basis. Within a stand, plots are typically "averaged" to create an inventory that represents the average condition for the stand. LMS uses this per area representation for inventory information. This inventory for the stand homogenizes variation within a stand; however, using one inventory per stand greatly decreases the amount of information that moves through the system. Individual plot information can be maintained by designing a portfolio that consists of stands with single inventory plots. The stand level perspective used by LMS allows for a balance between information representation and efficiencies associated with having fewer stands on the landscape.

LMS can also contain snag and down log inventory information, which is maintained as a separate inventory that includes species, diameter, height/length, snag/log per acre,

snag or log code, age (time since death or fall), and decay class. The snag and log inventory information is maintained and projected when the snag model is enabled in LMS configuration.

Future Inventory—Future inventories are maintained in the same format. The projected inventories are stored in separate directories for each projection period. While LMS is running, it maintains separate inventory files for each stand in each projection period. The future inventories are generated by the application of a growth model.

Spatial Information—In LMS, spatial information (digital elevation model and stand boundary map) is used for landscape visualization. The format of the spatial information is dictated by the requirements of the visualization tool. Spatial information can be combined with inventory information as part of down stream analyses that benefit from that kind of information. LMS does not currently provide automated links to GIS tools other than for landscape visualization.

LMS Activities

The use of LMS is organized into several activities: application management, growth simulation, silviculture and disturbance simulation, and outputs. Application management activities include accessing portfolios (Open, Close, Save, Backup, and Restore Portfolio, LMS Portfolio Editor; fig. 2a), LMS Configuration (fig. 2e), temporary file management (Flush and Remove Cache; fig. 2e), modification of inventory information (Edit Inventory File; fig. 2e), and modification of LMS Methods (Edit Methods; fig. 2e). Growth simulation includes the ability to grow one stand (Project Stand; fig. 2b) or the entire landscape (Project Landscape; fig. 2b). Silviculture activities allow for the manipulation of
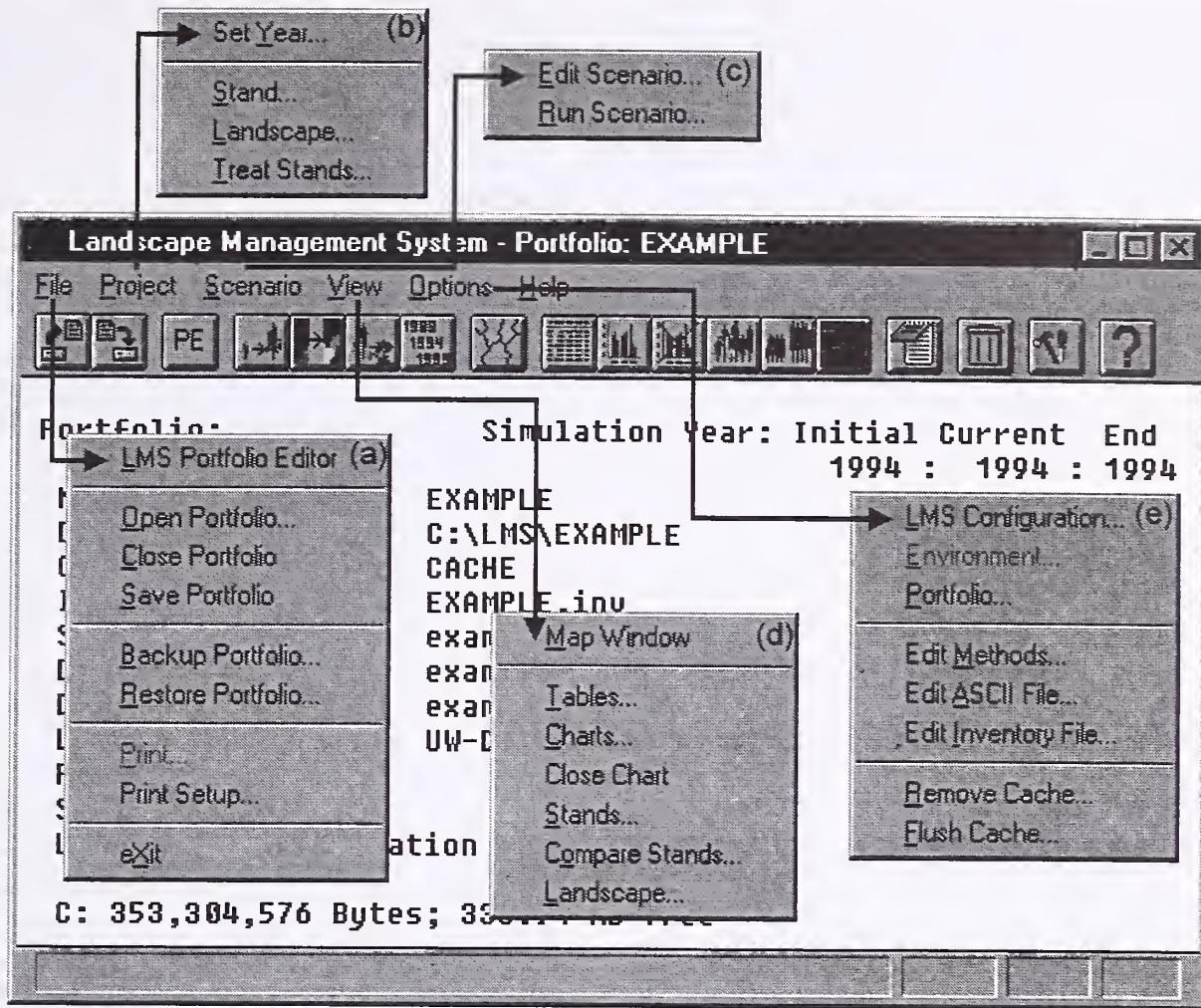
Figure 2—LMS main window showing menus: (a) File menu, (b) Project menu, (c) Scenario menu, (d) View menu, and (e) Options menu.

tree records (Project Treat Stands; fig. 2b). Output activities include the ability to display tabular information (View Tables; fig. 2d), a selection of charts (View Charts; fig. 2d), stand level visualization (View Stand, View Compare; fig. 2d), and landscape level visualization (View Landscas«; fig. 2d).

Growth Simulation

Vanclay (1994) suggests that models should be constructed so that it can be used as a "black box," which grows the stand one growth period. He is referring to designing the model in a modular way so as to separate the growth functions from the input/output routines. This same general approach is used by LMS. The entire growth model is abstracted and assumed to be this "black box."

Growth activities use the LMS Stand Projection Method to update stand inventories to a future condition. The Stand Projection Method is an abstraction of (in other words, hides details) and interface to existing growth models. It is implemented by the development of a general interface that operates by running "filter" programs. These filter programs provide inputs for various client programs or process outputs from client programs. Each growth model integrated into LMS requires a projection method and the filter programs used to convert information. The Stand

Projection method is applied once to update an inventory for a stand one time period.

Since the Stand Projection method consists of a general interface, additional processing can be added to the system simply by including more steps in the method. An example of this is the addition of a snag and down log simulator (CWDSIM). CWDSIM is integrated into the Stand Projection method by adding the processing of mortality predicted by the growth model. The mortality provided by the growth model is moved to separate snag/log inventory files. These separate snag/log inventory files are "projected" using CWDSIM. CWDSIM applies retention probabilities for snags by species, diameter, and age. Snags that are no longer retained are moved to the down log list. The same type of retention probabilities are used for down logs, moving them through decay classes until they disappear from the system.

The specific steps taken by the Stand Projection method are determined by a combination of portfolio information, user interaction, and the projection method. Portfolio information indicates the model and/or geographic variant of model that should be used by LMS to grow stands. The user interaction determines specific stands that are to be projected.

All stands on the landscape are grown using the Landscape Projection Method. The Landscape Projection Method is a special method that applies the Stand Projection method to grow each stand as it loops over all stands in the portfolio.
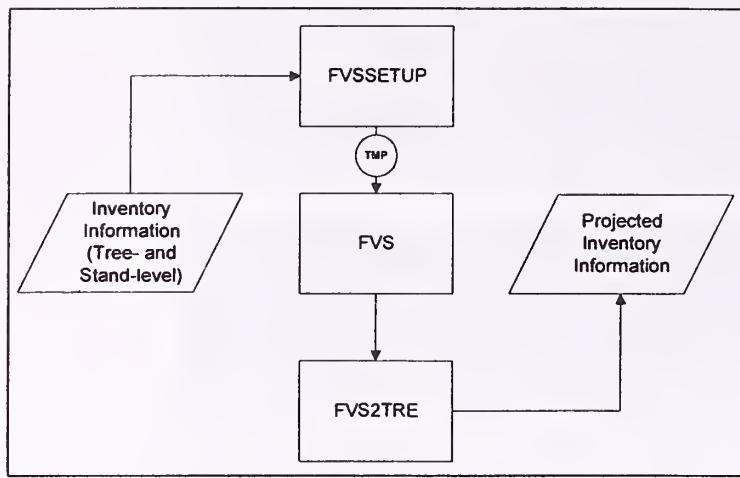
Figure 3—Stand projection method for FVS growth model. Intermediate temporary files are indicated with the TMP symbol.

One of the growth models integrated with LMS is the Forest Vegetation Simulator (FVS, Teck and others 1996; Wykoff and others 1982). The Stand Projection method (fig. 3) for FVS consists of two interface programs that have knowledge about FVS file formats. The input filter (FVSSETUP) is assigned the task of creating all input files necessary to run FVS (inventory file, keyword file, response file). The output filter (FVS2TRE) has the task of extracting information from FVS output files (output file, tree list file, and so forth).

Silviculture and Disturbance Simulation

Silvicultural operations and disturbance events are accomplished by manipulation or addition of tree inventory records. The manipulation of tree inventory records is done separately from the growth model by an external treatment filter (TRTSTAND, fig. 4). This program reads existing inventory files, and based on input from the treatment dialog simulates the treatment or disturbance by manipulating those tree records.

The options currently supported by the treatment filter include thinning to target TPA, percent of original, basal area, and Reineke (1933) Stand Density Index (SDI). These treatments can be modified by species selection (include or exclude) and diameter limits (minimum and maximum). The ability to introduce new inventory information (plant and ingrowth) is also included.
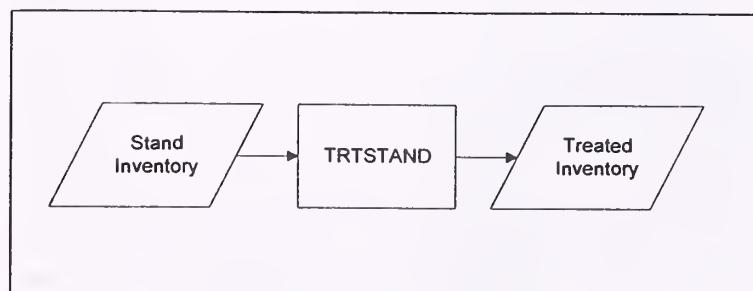
Figure 4—Silviculture and disturbance process.

LMS is being modified to allow FVS to be used for silviculture and disturbance simulation. This will be implemented as an option in Run Scenario, using a new scenario file format that specifies FVS keyword files for each stand.

Output

To effectively communicate, a software system needs to provide a wealth of outputs that allow the user to observe the information contained in the system. LMS outputs include tables, charts, and visualizations. The tabular outputs can be sent to a text editor, spreadsheet, or a file for later use. The creating of files for later use allows the user to use whatever analysis software they want to make subsequent examinations of the inventory information.

Tabular Output—Tabular outputs are any output from the system that can be presented as a table of numbers. These include inventory records, stand summary statistics, and stand attributes.

Two approaches can be taken in regards to tabular outputs. An inclusive approach would identify the specific information and statistics and only include these in the system. LMS has a more open approach. We recognize that the system cannot provide the computations desired by all users since we don't know the questions that users will be asking about their stands and landscapes. The focus of LMS has been to provide ways to get the inventory information into external analysis tools (spreadsheets, databases, statistical packages, and so forth) so that the user can perform the computations they need for their analysis. This provides an environment where the system does not constrain the possible analysis; rather, the analysis is only constrained by the ability and imagination of the user.

Several example analyses are distributed with LMS. These analyses are implemented in software not distributed with LMS (external tools) to serve as examples of the types of external analyses that can be performed on LMS outputs. The use of the external tools is efficient in one sense because it brings more talent into the analysis arena, rather than just the programmer. As analyses in external tools become generally useful and stable, they can be re-implemented by programmers to make them more computationally efficient and robust. The examples provided with LMS include stand summary statistics and stand structure stage classification implemented in Microsoft Excel along with stand structure stage classification, standing volume, and wind hazard risk implemented in Microsoft Access.

Graphical Output—Graphical output can often be a very effective means of communication. Several charts are currently provided that provide quick examination of diameter and height distributions.

Visualization Output—The emergence of scientific visualization and recognition of the effectiveness of communication through pictures make visualization a very attractive component of the system. Two resolutions are logical: stand level and landscape level. Stand level visualization presents a view of an average acre of a stand. Landscape level visualization provides a view of activities on the landscape and relative differences between stands.

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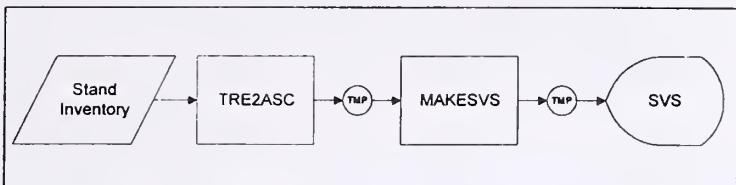
Figure 5—Stand visualization process. Intermediate temporary files are indicated with the TMP symbol.

Each resolution of visualization is useful in communicating specific information about the stands and landscape. Although intriguing, visualization may not be the most appropriate means of communicating some types of information (for example, stand visualization is not good at communicating how many trees of a given size are in the stand).

Stand Visualization

The inventory information in LMS that is useful for stand visualization includes species, diameter, height, crown ratio, and trees per acre. Stand visualization requires the generation of tree locations to distribute the trees across the acre and crown width information to display trees. The Stand Visualization System (SVS, McGaughey 1997) is used for stand visualization in LMS. The inventory information is converted to an intermediate file format by TRE2ASC (fig. 5). MAKESVS then creates the file displayed by SVS, generating spatial coordinates using a random algorithm. MAKESVS generates uniform random numbers that are converted to tree locations for the visualization. If a tree already occupies the location, another set of random numbers are obtained. The search for an open location is attempted up to 10 times before the tree is placed at the last location tried. The algorithm can be thought of as being random with repulsion. The results of visualization are shown in figure 6.

Landscape Visualization

The inventory information in LMS that is useful for landscape visualization includes species, height, and trees per acre. Landscape visualization is a combination of inventory information with spatial information. The landscape visualization software used, UVIEW, is part of the UTOOLS Watershed Analysis and Visualization software (Agar and McGaughey 1997). UVIEW requires a digital terrain model (.DTM), spatial database (.DB), and structure database (.DB) to render inventory information on the landscape. Landscape level visualization requires the conversion of spatial information to file formats for UVIEW.

UVIEW requires a PC-PLANS binary digital terrain model (DTM) format. This file can be created from a USGS 7.5 minute Level 1 DEM format file using IMPRTDEM from UTOOLS. The spatial database is a Paradox database that can be created from a MOSS Vector file containing stand boundaries using UCELL5 from UTOOLS. The structure database is created "on the fly" by components of LMS. Assuming that the elevation model and spatial database are already constructed, the process of creating a landscape visualization is below. Landscape visualization tools need less information than the full inventory.
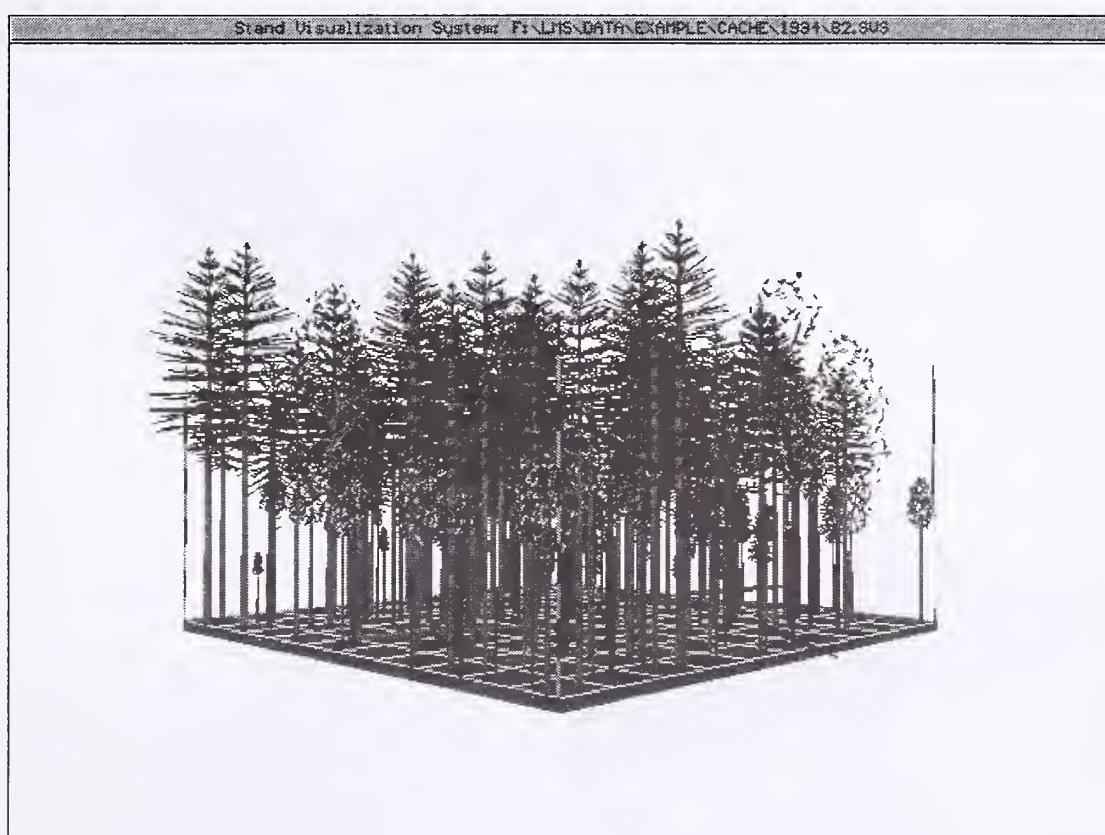
Figure 6—Example of stand visualization.
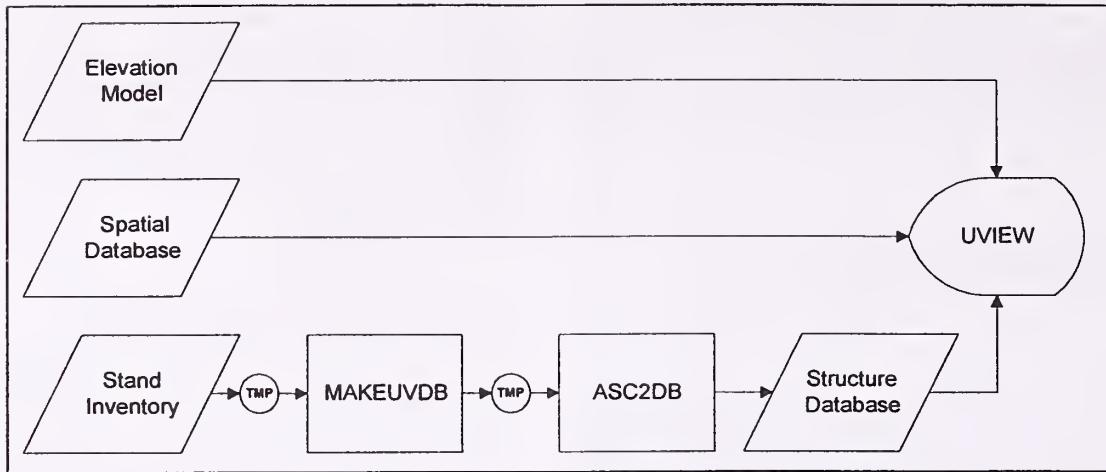
Figure 7—Landscape visualization process. Intermediate temporary files are indicated with the TMP symbol.

The process for landscape visualization is shown in figure 7. Stand inventory information is combined and processed by MAKEUVDB to create the information for the structure database. The output from MAKEUVDB is converted to a Paradox database by ASC2DB. UVIEW is then used to combine the spatial information and structure database to produce the visualization. Since UVIEW cannot represent all of the inventory information on the landscape, MAKEUVDB performs a classification of the original inventory information by grouping the inventory information (single group, hardwood/conifer groups, or species groups) and then looking for "layers" within the groups. It computes the mean height and variance for each combination of layer and group. The results of landscape visualization are shown in figure 8.

Example Analyses

Projected inventory information can be exported from LMS and used in a variety of analysis tools. This section presents several examples of the types of external analyses that are possible.

Standing Volume

Alternative management regimes can be evaluated by comparing standing volume between regimes. Figure 9 compares how standing volume changes under no management versus a thinning scenario.
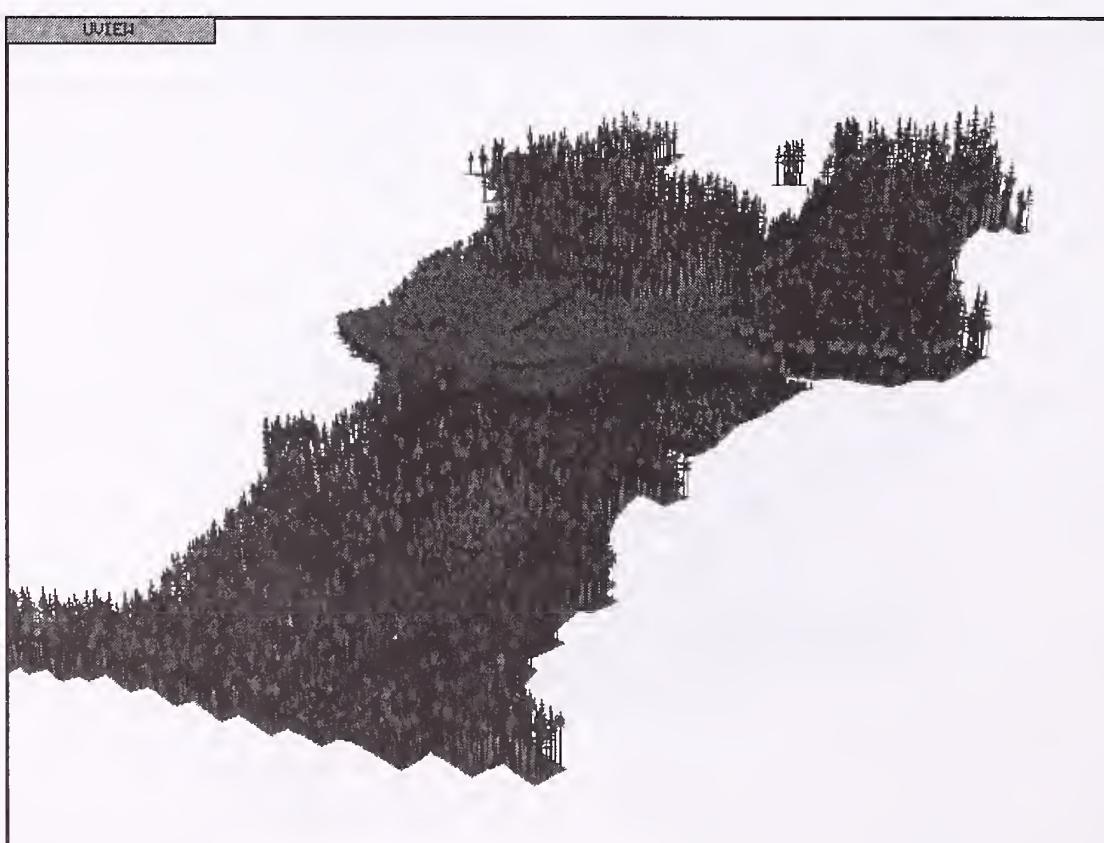
Figure 8—Example landscape visualization.
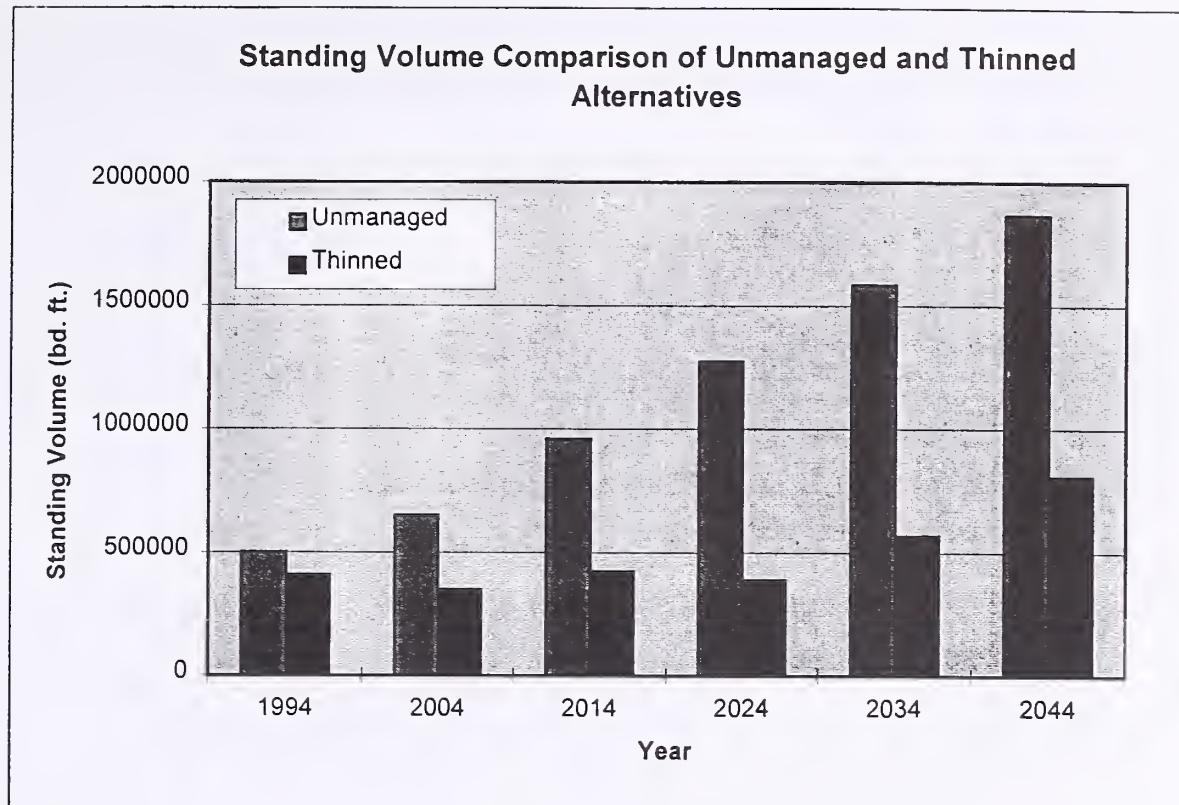
Figure 9—Standing volume comparison of two alternative management regimes.

Density Management

Density management diagrams are useful for evaluating stand changes over time. For an example see Long and others (1988). This diagram can be simplified by removing the height and volume lines, leaving the Reineke (1933) SDI lines for reference (fig. 10). Diagrams like this are extremely useful for evaluating output from growth models. They
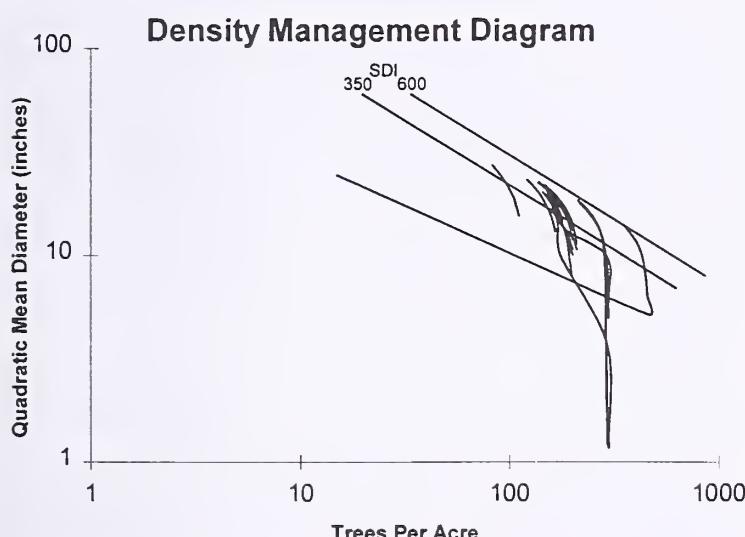
Figure 10—Density management diagram created in Microsoft Excel using the landscape summary table from LMS. Density management diagrams show the change in quadratic mean diameter and trees per acre over time. Self thinning stands move up and bend to the left. Thinned stands shift left and then continue moving upward. Stands with regeneration or ingrowth move down and to the right before continuing upward.

provide a comparison to stand development and self-thinning theory.

Young stands typically start with a large number of individuals. As they develop, the quadratic mean diameter increases as all the trees get larger. Individual trees will occasionally die through mortality and disturbance. At some point in the development of the stand, trees begin to die due to the competitive stress from other trees. A self-thinning stand moves from the lower right up toward a maximum size-density line and as it approaches the maximum line it curves to the left to approximately parallel the maximum line. Comparison of actual or simulated stands to the stylized self-thinning line gives insight to changes occurring in stands.

The lines in this diagram (fig. 10) represent simulated changes to individual stands through time. Stands that are self thinning approach the maximum reference line and gradually curve over to parallel the SDI lines. Lines that shift left abruptly indicate stands that are thinned. Lines that move back to the right indicate stands that have new individuals introduced via ingrowth or planting.

Stand Structure

Various stand structure classifications can be used to evaluate stand conditions and potential habitat. There have been many forest stand structural classifications proposed. Most of these schemes are not practical classifications since they are not quantitative or do not define mutually exclusive categories. The development of automated techniques for classifications require that the algorithms need to operate on the inventory information available and that the classification rules result in unique results. Figure 11 presents a simple classification of LMS output based on four stand structural classes proposed by Oliver (1981).
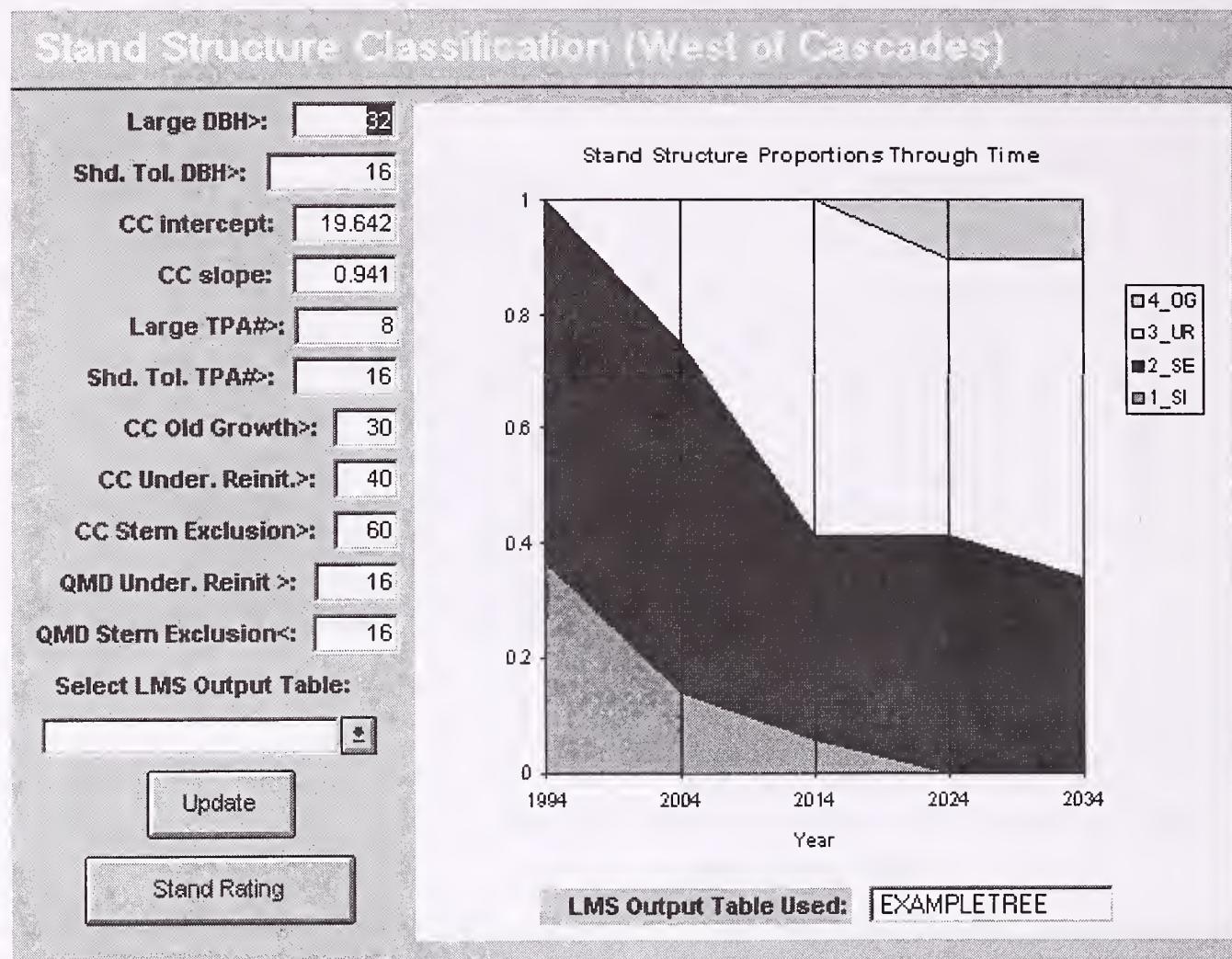
Figure 11—Example stand structural classification.

Wind Hazard

Risk of natural disturbance events (for example, wind, fire, and insect) can be evaluated based on projected inventories for the stand and landscape. Figure 12 shows a wind hazard classification for a projected landscape. This wind hazard classification is based on soil, exposure, and stand attributes. In addition, the structure of upwind forest stands are considered.

Conclusions

Integrating software into other systems can have effects on the results from that software. When a program is taken out of its design environment (different operating system, different data source, and so forth), results from the program may be influenced. Running FVS interactively within LMS influences the results of simulation. FVS was designed to load the inventory information once at the beginning of the simulation. LMS removes the inventory information at the end of each cycle, making it available for viewing and manipulation. Extracting and reloading the inventory information influences the growth results because FVS is not able to take advantage of the history of growth. LMS is being modified to provide support for running FVS while loading the inventory information only at the beginning of simulation.

Improved integration of growth models with LMS will provide more options for controlling the simulation to achieve the projections needed by the user. Growth models need to be improved to include broader ranges of stand and treatment conditions to make them increasingly useful for simulation of alternative management techniques. Enhancements to LMS outputs are being developed that will allow for flexibility in creating tables that include only the information desired by the user. Improvements to visualization methods are also being investigated. Additions of simulation of other attributes is desirable, but with the absence of models for these attributes an after simulation analysis may be most productive.

In LMS these "down-stream" analyses frequently use classification. The results of these analyses are strongly influenced by the sensitivity of the classification schemes used. The results of structural stage classifications or hazard classifications are extremely dependent on the criteria used in separating the classes. Specific classification schemes may be very dependent on the information used to develop them and may not be portable between diverse areas.

This system demonstrates some of the potential for improvement in user interfaces in our modeling efforts. It is possible to build larger integrated systems that incorporate diverse software by providing for the details of communication between software. It is also possible to build

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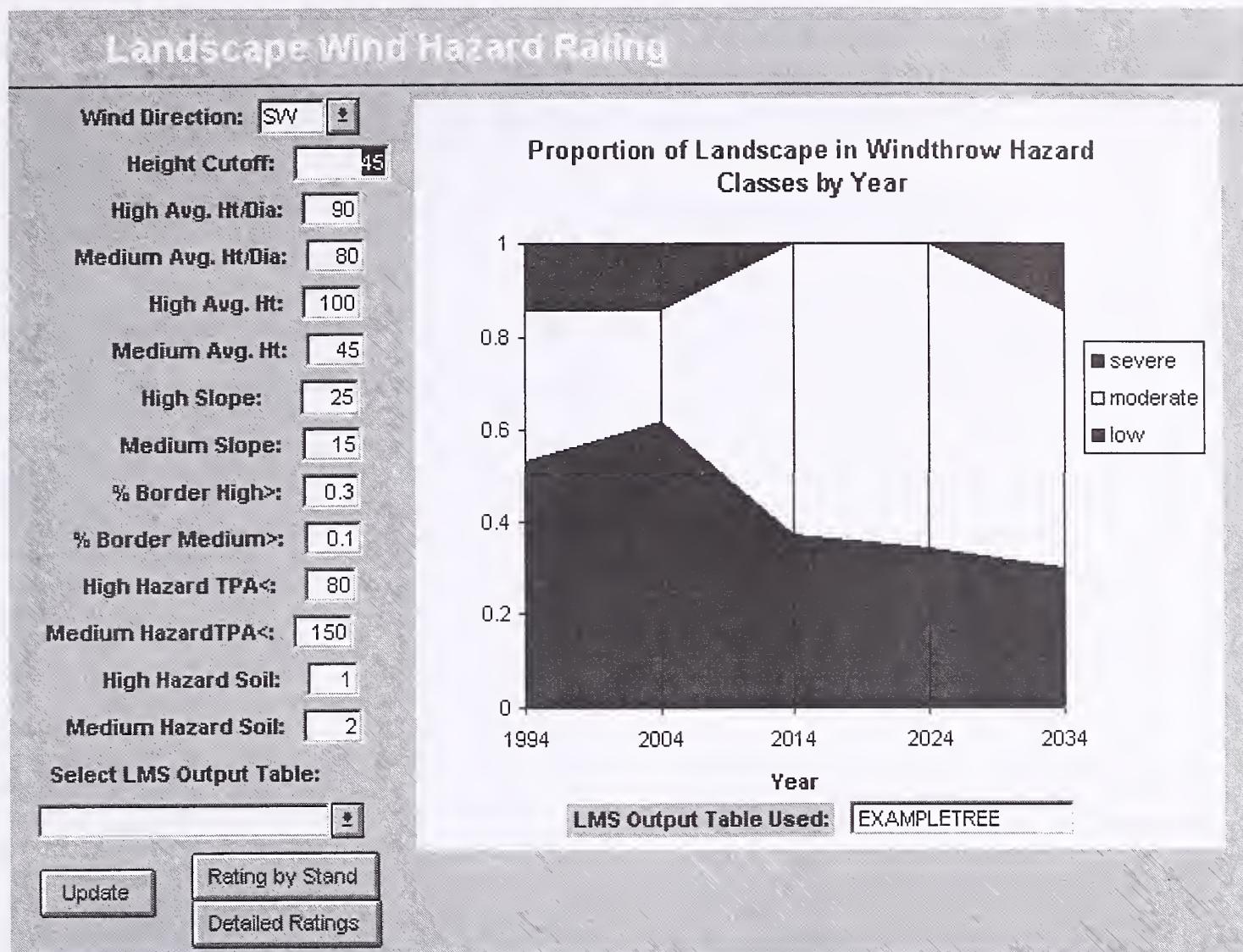
Figure 12—Example wind hazard analysis.

open and flexible systems that are adaptable, allowing users of the system to address new situations as they arise. The simplified user interface makes it possible for more people to run simulation models and perform simulation based experiments. Making it easier to run growth models does not absolve the user from learning the details of the growth model to assure the appropriate use and interpretation of modeling results.

LMS is available by contacting the author. Contact information is included in the author footnote.

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FVSSTAND Alone:
Generate Dynamic Yield Reports from the Forest Vegetation Simulator

Don Vandendriesche

Abstract—FVSSTAND Alone is a post processor program that produces standard stand and stock tables and much more from the Forest Vegetation Simulator (FVS). Species-size class reports are generated that can be used for forest type designation, structural stage forecasting, and product merchandizing. Two types of yield reports are available, time dependant and age dependant, specifically designed for importation into forest planning models. The ability to embed localized tree volume equations into the program is an added benefit. Stand visualization features that include the development of a dynamic movie of the simulated stand profile are an automatic feature. FVSSTAND Alone is a valuable addition to any forest analyst tool kit. Don't leave FVS without it!

The need to generate stand and stock tables from Forest Vegetation Simulator (FVS) treelist output files originated from a management planning project on the Flathead Indian Reservation. The FVS model was used to forecast existing and regenerated stand structures over time to aid in the development of yield profiles. After reviewing the standard output tables from FVS, it became evident that species specific information by size class would be difficult to obtain. Percentile data is of little use in the application of silvicultural regimes for planning purposes. Thus, the development of a stand table program that would interface with Forest Vegetation Simulator treelist at each projection cycle was pursued (Vandendriesche 1993).

The FVS model produces pre- and post-treatment tree lists at specified time intervals for a given management prescription. Each tree record contains species, diameter, height, crown ratio, and other tree attribute information. Stands represented by field inventory data from permanent plots or temporary points are grown individually by FVS and summarized via the FVSSTAND program. Either of two types of yield reports can be generated: Time Basis Yields or Age Basis Yields. Time-based yields are generally associated with all-aged stands or homogeneous stand types. Coefficients are reported as a function of time. Age-based yields are generally associated with even-aged stands. Values

are displayed as a function of stand age. Reports generated from FVSSTAND are available in two forms. First, stand tables for stocking, growth, harvest, and mortality by species are arrayed by 2 inch d.b.h. classes. Second, summary tables by size class are produced. An added feature of FVSSTAND is the creation of flat files (ASCII based/column delimited) for importation into forest planning models. Yield streams from FVSSTAND have been successfully imported into the SARA/C-WHIZ (Davis 1990) and TEAMS (Wood 1988) planning models. Developing a compatible file format with the SPECTRUM (Sleavin 1996) model is being actively pursued. Currently, forest cover type, vegetative structural stage, stand density index, tree frequency, quadratic mean diameter, basal area, cubic foot, and board foot data can be exported from the stand and stock tables. Tree species and user-specified size class breaks form further subdivision of this information. Links to the Stand Visualization System (SVS) (McGaughey 1996) provide a graphical depiction of the stand at various points in time or age.

Prior to Program Execution

A few limitations and restrictions need to be presented. The FVSSTAND program is written in Ryan/McFarland FORTRAN. It is designed for the personal computer (PC) platform. FVSSTAND runs as a DOS application in the Microsoft Windows 3.1 or Windows 95 environment. The latest version of FVSSTAND is based on Version 6.2 of the Forest Vegetation Simulator. Primary development emphasis has been placed on the Inland Empire, Central Rockies, and Lake States Variants. The FVSSTAND program has been successfully applied to forest management planning projects on the Flathead Indian Reservation in western Montana, the Navajo Nation in northeast Arizona, and the Menominee Reservation in central Wisconsin. There are 20+ FVS Variants that cover most forested areas within the United States. Additional model variants are being pursued in the United States, Canada, and abroad. Operational FVS Variants are available from the U.S. Department of Agriculture, Forest Service, Forest Management Service Center, Fort Collins, CO (www:htp://162.79.41.7).

FVSSTAND users must create treelist output files from FVS by using the keywords "TREELIST" and "CUTLIST" in their keyword files. These keywords can be added using a text editor, the FVS Submittal System (Teck 1996), or SUPPOSE (Crookston 1997). Treelist output files must have an extension name of ".LST" (for example, WPWP120.LST). The keyword "TREELIST" should contain a 0.0 in the first field (output all cycles), a 1.0 in the third field (produce -999 header record), a 0.0 in the fifth field (generate a mortality

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treelist), and a 0.0 in the sixth field (utilize FVS Version 6.2 output format). The keyword "CUTLIST" must also be present and have the exact field designations as the "TREELIST" keyword. This combination of "TREELIST" and "CUTLIST" keywords will produce the desired treelists for FVSSTAND. The current program version is able to handle 'tripling', 'compressed', and newly 'established' tree records. An example keyword file that takes advantage of the "ADDFILE" keyword option is presented in figure 1.

Behind the Scene

FVS_LNK is a support program written in Microsoft QuickBasic. It is required to run prior to FVSSTAND execution. FVS_LNK reads the individual FVS treelist output files and creates a link file and tree file. The FVS.LNK file is a concatenated, sequential listing of the header records from the individual treelist files. The FVS.TRE file is a concatenated, sequential listing of the tree records from the individual treelist files. Appended to the end of the normal FVS treelist header record are several additional items such as: Stand Type (extracted from the keyword files); Stand Age (extracted from the summary output file); Age Class Indices for 5, 10, and 15 year intervals (calculated from stand age); Site Index (extracted from the keyword file); Stand Density Index (extracted from the summary output file); and Tree File Link (index to FVS.TRE file). The age class indices allow specification of age breaks in either 5, 10, or 15 year intervals. The tree file link provides direct access capability to the tree information from the header records enabling fast processing of tree records.

There is no limitation on the number of stands that can be handled by FVS_LNK and subsequently by FVSSTAND. The only limitation is the size of the hard disk employed.

```
SCREEN
STATS
STDIDENT
PLT00###   WPWPXX01 --> CT=WHITE PINE / FT=WHITE PINE / HT=All / Rx=1st WP Prescription
DESIGN          -5.0   100.0     5.0     1.0
GROWTH           1.0     9.0     1.0     9.0     9.0
STDINFO        906.0     0.0     0.0     0.0     5.0    17.0    45.0
SITECODE         2.0    60.0
INVYEAR       1988.0
NOAUTOES
CALBSTAT        50
OPEN            50       0       0
PLTXXXXX.CAL
BFVOLUME      1988.0            11.0    10.0     1.0    80.0
VOLUME        1988.0             5.0     4.5     1.0    80.0
MCDEFECT                 1      0.06    0.18    0.00    0.00    0.00
MCDEFECT                 3      0.04    0.04    0.03    0.03    0.03
BFDEFECT                 1      0.00    0.21    0.00    0.00    0.00
BFDEFECT                 3      0.00    0.05    0.04    0.18    0.03
READCORD
     0.696    1.000   0.417   1.000   0.918   1.000   1.000   2.047
     1.500    2.235   1.000   1.673   1.000   1.000   0.960   1.000
****************************
* add prescription file *
****************************
OPEN            40.0
PW_CL.KEY
ADDFILE         40.0
NOTRIPLE
TREEDATA
TREELIST         0.0             1.0     0.0     0.0     0.0
CUTLIST          0.0             1.0     0.0     0.0     0.0
ECHOSUM
MGMTID
MENO
COMMENT
END
PROCESS
STOP
```

Figure 1—Example TREELIST/CUTLIST keywords in FVS keyword file.

Individual FVS treelists are read consecutively. As one stand is processed by FVS_LNK, its associated treelist, main output, and summary output files are deleted, thus freeing up disk space. FVSSTAND utilizes the FVS.LNK and FVS.TRE files for further processing of output products.

Modes of Operation

There are two methods for running the FVSSTAND program: as a stand alone executable or as a batch processor. The interactive screen shown in figure 2 will appear when FVSSTAND is entered at the DOS prompt or in the 'FILE/RUN' option in Windows. Enter the input parameters as requested. The projection title documents the particular run and will be printed at the top of each output page. Stand type is an optional parameter. If not supplied by the user, it will be inferred from the STDIDENT keyword. Stand tables are compiled by "Softwood Species," "Hardwood Species," and "All Species" by choosing the combined option for species report. Selection of the complete option will prompt FVSSTAND to compile stand tables for each individual species including softwood, hardwood, and all species. Thus, the combined species selection produces an abbreviated composite report. Footnotes will appear on the banner pages of the output stand tables. If age basis yield reports are requested, a second prompt soliciting the age interval will appear. Potential selections are: 5, 10, and 15 year age classes. Links to the Stand Visualization System (SVS) provide a graphical depiction of the stand at various points in time or age.

A second method of operating FVSSTAND is to edit a 'Response File' and run in batch mode. Refer to figure 3. A generic file 'FVSSTAND.IN' can be modified and piped directly as input to FVSSTAND. There are two response files that coincide with the option for time and age basis yields. They are entitled "FVSSTAND.TIM" for time and "FVSSTAND.AGE" for age. A batch file named "FVS2STD.BAT" is designed to handle these response files. Type FVS2STD at the DOS prompt to begin batch processing. FVS_LNK will appear on the screen. When finished, a menu requesting selection of time or age basis yields will

```
GENERATE STAND TABLES FROM FOREST VEGETATION SIMULATOR TREELIST

INPUT PARAMETER SCREEN


Projection Title: Forest Management Plan Analysis

Stand Type (optional): WPWP

Combine = 1 // Complete = 2 Species Report: 1

Footnote #1: White Pine Cover Type --> White Pine Featured Type

Footnote #2: Shelterwood Silvicultural Prescription


Time Basis = 1 // Age Basis = 2 Yield Report: 2

Age Interval (5/10/15 yr): 5


SVS Linkage (Y/N): Y
```

Figure 2—Stand alone executable mode—entry screen prompts.

FVSSTAND.EXE < FVSSTAND.IN

```
Forest Management Plan Analysis
STY
1
Note 1: Timberland Stand Type
Note 2: Silvicultural Prescription - Let Grow / No Treatment
1
5
N
```

Figure 3—Batch processing–response fire setup.

appear. Following selection, FVSSTAND will execute. To modify a response file, simply use your favorite text editor and make the desired changes.

Following Program Execution ____

Printouts generated by FVSSTAND are available in two forms. First, stand tables for stocking, growth, harvest, and mortality by species are arrayed by 2 inch d.b.h. classes (refer to table 1). Second, summary tables that depict stocking, growth, harvest, and mortality by species are arrayed by size class (refer to table 2). This is an abbreviated version of the first output based on the subtotal array elements. Size class breaks are a variable in FVSSTAND and can be adjusted to fit specific needs.

Stand tables produced from FVSSTAND hold a wealth of information. Previous stocking values are displayed to the left of the present stand condition. Annual growth rates are presented to the right relative to beginning diameter class. Defect percent is listed in terms of board volume. Harvest and mortality tables complete the accounting of net change. Knowing the stocking in the previous period, adding growth components, and subtracting losses due to harvest and mortality render the present stand structure. Each of these components is readily available in the FVSSTAND printouts. Interpretation of FVS model results can be easily tracked and efficiently validated.

Printouts are labeled with the "Stand Type" comprising the first four characters of the file name. The stand type is derived from the stand identification keyword (STDIDENT), columns 11 through 14. For time basis yield reports, the next two digits following the stand type represent the projection cycle. A "01" coding would indicate the first projection cycle, whereas a "10" would indicate the tenth projection cycle. For age basis yield reports, the next digit following the stand type designates the origin of the stand. A code equal to "0" signifies the existing stand. A code equal to "1" signifies the first regenerated stand. A code equal to "2" signifies the second regenerated stand. Subsequent stand origin codes follow a similar pattern. The next two digits following the stand origin indicate the age class. Age class codes are multiples of the age interval. For example, a "10" age class designation (5 year interval) would represent the 50 year old age class. A "20" would represent the stand at age 100 years.

The file extension indicates a diameter class printout (.PT1) versus a size class printout (.PT2). Example directory file listings follow:

Time Basis Yield Reports
 White Pine/White Pine Stand Type
 Time Period Projection 5 year interval)

>dir *.pt1 (diameter class printout)

 Volume in drive F is HARD_DISK_F
 Volume Serial Number is 1C32-4E2E
 Directory of F:\FVS

WPWP00	PT1	35,771 04-25-97	6:17p	—\
WPWP01	PT1	35,771 04-25-97	6:17p	|
WPWP02	PT1	35,771 04-25-97	6:18p	|
WPWP03	PT1	35,771 04-25-97	6:18p	|
WPWP04	PT1	35,771 04-25-97	6:18p	\
WPWP05	PT1	27,778 04-25-97	6:18p	}—Projected Stand Structure
WPWP06	PT1	23,848 04-25-97	6:18p	/ Time Period 0 to 60 years
WPWP07	PT1	31,841 04-25-97	6:18p	|
WPWP08	PT1	35,771 04-25-97	6:18p	|
WPWP09	PT1	35,771 04-25-97	6:18p	|
WPWP10	PT1	35,771 04-25-97	6:18p	|
WPWP11	PT1	35,771 04-25-97	6:19p	|
WPWP12	PT1	35,771 04-25-97	6:19p	—/

 13 file(s)   1,383,148 bytes

Age Basis Yield Reports

 White Pine/White Pine Stand Type
 Age Class Projection (5 years interval)

>dir *.pt2 *(size class printout)*

 Volume in drive F is HARD_DISK_F
 Volume Serial Number is 1C32-4E2E
 Directory of F:\FVS

WPWP028	PT2	17,765 04-25-97	6:17p	--\
WPWP029	PT2	15,034 04-25-97	6:18p	} Existing Stand\Origin = 0
WPWP030	PT2	15,034 04-25-97	6:18p	--/ Age Class 140 to 150 years
WPWP100	PT2	15,034 04-25-97	6:18p	--\
WPWP101	PT2	15,034 04-25-97	6:18p	|
WPWP102	PT2	9,572 04-25-97	6:18p	|
WPWP103	PT2	15,034 04-25-97	6:18p	\
: :	:	: :	:	:}— Regenerated Stand\Origin = 1
WPWP127	PT2	35,528 04-25-97	6:23p	/ Age Class 0 to 150 years
WPWP128	PT2	35,528 04-25-97	6:23p	|
WPWP129	PT2	35,528 04-25-97	6:23p	|
WPWP130	PT2	28,689 04-25-97	6:23p	--/
WPWP200	PT2	28,689 04-25-97	6:23p	--\
WPWP201	PT2	28,689 04-25-97	6:23p	}-- Regenerated Stand\Origin = 2
WPWP202	PT2	9,572 04-25-97	6:23p	--/ Age Class 0 to 15 years

 41 file(s)   1,137,822 bytes

"FLAT FILES" for Forest Planning Models

An added feature of the FVSSTAND program is the creation of flat files (ASCII based/column delimited) for importation into forest management planning models. Currently, vegetative structural stage, stand density index, tree frequency, quadratic mean diameter, basal area, and volume attributes can be exported from the stand and stock tables. Tree species and size class can form further subdivisions of this information. Structured formats have been developed for the SARA/C-WHIZ and TEAMS forest models. Contacts have been made with the U.S. Department of Agriculture, Forest Service, Ecosystem Management Analysis

Center staff in Fort Collins, CO, to develop links to the SPECTRUM model. Formatted yield tables can be developed from the flat files. Utilizing commercial spreadsheet software enables development of user preferred table formats. Table 3 displays an example of a time basis yield table. Table 4 displays an example of an age basis yield table.

Stand Visualization System Linkage

Stand Visualization System input tree files will be automatically generated from the composite stand tables if SVS linkage is requested. A 'DRAW.BAT' file is created that contains the commands to run SVS. Appropriate tree list files are called and a PCX graphic depiction of the stand is developed. A 'MOVIE.LST' file is also created that contains the names of the PCX files. Lastly, a 'VIEW.BAT' file is created to be used in conjunction with the 'MOVIE.LST' to show realistic animation of the stand through time.

Future Program Developments

In the near future, handling variants from other regions will be addressed. Additional regional vegetative structural stage classifications will be included as they are formulated. Attributes that can be derived from stand structure such as fire risk rating, pathogen indices, and wildlife habitat will be added. Conversion of FVS_LNK and FVSSTAND to a

Windows-based platform is also being considered. Porting to the IBM AIX/UNIX operating system will be pursued. Requests from the user community will dictate the future direction of FVSSTAND. If there is a need for this software, do not hesitate to give me a call at (970) 498-1781. All comments or suggestions are welcome.

References

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Table 1—FVS Stand Table—Diameter Class Arrayed. (WPWP030.PT1)

--- Forest Management Plan Analysis

DATE RUN - 04/08/1997
PLOT ACRES - 26.00
MEASUREMENT LENGTH - 5.00 YEARS

TABLE 1-1 S T O C K ,   S T A N D ,   A N D   G R O W T H

--- All Species Combined

DIA. CLASS:	:---- 146 M E A S U R E M E N T					----:---- 150 M E A S U R E M E N T					----:- A N N U A L G R O W T H -:					%
	FREQ /AC	AVG DBH	BA /AC	CU /AC	BM /AC :	FREQ /AC	AVG DBH	BA /AC	CU /AC	BM /AC :	DIA INC	BA /AC	CU /AC	BM /AC :	DEF
2. :	91.57	2.32	2.735	0.00	0.0 :	73.78	2.41	2.377	0.00	0.0 :	0.062	0.174	0.00	0.0 :	0.00
4. :	45.17	3.83	3.695	0.00	0.0 :	51.69	3.80	4.148	0.00	0.0 :	0.212	0.627	21.70	0.0 :	0.00
SUB. :	136.74	2.82	6.431	0.00	0.0 :	125.47	2.98	6.525	0.00	0.0 :	0.111	0.801	21.70	0.0 :	0.00
6. :	2.63	6.26	0.565	7.62	0.0 :	5.54	5.52	0.933	18.07	0.0 :	0.065	0.012	0.24	0.0 :	0.00
8. :	2.99	7.89	1.019	20.21	0.0 :	7.38	8.26	2.760	66.58	0.0 :	0.064	0.017	0.41	0.0 :	0.00
10. :	2.64	10.03	1.453	34.81	0.0 :	5.86	9.76	3.055	82.83	0.0 :	0.161	0.052	1.46	6.9 :	0.00
SUB. :	8.26	8.06	3.037	62.65	0.0 :	18.78	7.92	6.748	167.47	0.0 :	0.095	0.080	2.11	6.9 :	0.00
12. :	4.29	12.00	3.376	82.94	213.1 :	3.75	12.10	2.995	75.91	203.8 :	0.110	0.064	1.80	8.0 :	0.13
14. :	3.20	13.85	3.353	88.40	293.9 :	2.92	13.86	3.061	77.74	251.8 :	0.172	0.086	2.58	12.9 :	0.16
SUB. :	7.49	12.79	6.729	171.34	507.0 :	6.66	12.87	6.057	153.65	455.6 :	0.136	0.150	4.38	20.9 :	0.14
16. :	5.08	15.91	7.014	202.83	875.4 :	5.01	16.00	7.003	196.82	830.9 :	0.141	0.127	3.98	23.3 :	0.12
18. :	4.79	17.83	8.318	244.56	1416.0 :	4.51	17.84	7.838	232.90	1224.7 :	0.164	0.157	4.67	36.4 :	0.11
20. :	5.66	19.84	12.155	363.09	2270.1 :	6.00	19.95	13.047	391.64	2446.5 :	0.148	0.186	5.52	45.9 :	0.15
22. :	3.60	21.85	9.371	272.00	1723.0 :	4.27	21.94	11.221	321.92	2115.8 :	0.151	0.133	3.99	31.9 :	0.15
24. :	5.30	23.90	16.520	480.26	3434.9 :	4.03	24.05	12.719	367.07	2646.3 :	0.306	0.536	17.98	125.4 :	0.12
26. :	5.68	25.94	20.838	596.17	4269.8 :	6.31	26.08	23.420	676.98	4920.2 :	0.140	0.228	6.67	58.3 :	0.12
28. :	5.23	28.02	22.426	642.71	4694.2 :	4.20	27.95	17.894	513.52	3760.8 :	0.141	0.228	6.80	56.5 :	0.13
30. :	3.01	29.80	14.571	401.91	3347.4 :	4.81	29.81	23.308	660.77	5175.4 :	0.137	0.136	3.70	36.0 :	0.13
32. :	2.33	31.48	12.593	358.19	2991.9 :	2.75	31.88	15.225	425.31	3573.9 :	0.138	0.111	3.19	29.8 :	0.13
34. :	1.24	33.65	7.673	221.59	1842.3 :	1.24	34.06	7.852	225.79	1895.2 :	0.131	0.060	1.77	16.1 :	0.13
36. :	0.93	35.94	6.575	185.00	1621.7 :	0.93	36.14	6.650	187.56	1638.6 :	0.128	0.047	1.36	12.6 :	0.13
38. :	0.94	37.94	7.358	220.06	1723.2 :	0.75	37.83	5.853	176.00	1354.8 :	0.120	0.047	1.49	11.9 :	0.13
40. :	0.17	46.80	2.052	58.80	520.1 :	0.73	43.21	7.472	231.31	1765.6 :	0.080	0.007	0.21	1.8 :	0.10
SUB. :	43.95	24.10	147.464	4247.17	30729.8 :	45.53	24.59	159.504	4607.58	33348.9 :	0.163	2.003	61.33	485.8 :	0.13
TOTAL:	196.45	8.18	163.661	4481.15	31236.8 :	196.45	8.80	178.834	4928.70	33804.4 :	0.123	3.035	89.51	513.5 :	0.13

TABLE 1-4 H A R V E S T   A N D   M O R T A L I T Y

--- All Species Combined

	:---- A N N U A L H A R V E S T						----:---- A N N U A L M O R T A L I T Y						----:
:	FREQ. /AC	AVE. DBH	BA /AC/YR	NET CU /AC/YR	NET BD /AC/YR	% BD DEF	GR. BD /AC/YR :	FREQ. /AC	AVE. DBH	BA /AC/YR	NET CU /AC/YR	NET BD /AC/YR	% BD DEF	GR. BD /AC/YR :
2. :	0.00	0.00	0.000	0.00	0.0	0.00	0.0 :	10.30	2.29	0.060	0.00	0.0	0.00	0.0 :
4. :	0.00	0.00	0.000	0.00	0.0	0.00	0.0 :	2.01	3.83	0.033	0.00	0.0	0.00	0.0 :
SUB. :	0.00	0.00	0.000	0.00	0.0	0.00	0.0 :	12.32	2.55	0.093	0.00	0.0	0.00	0.0 :
6. :	12.50	5.48	0.413	8.88	0.0	0.00	0.0 :	0.13	6.22	0.006	0.08	0.0	0.00	0.0 :
8. :	3.77	7.92	0.259	5.80	0.0	0.00	0.0 :	0.19	7.78	0.013	0.28	0.0	0.00	0.0 :
10. :	1.41	10.29	0.163	3.79	0.0	0.00	0.0 :	0.12	9.88	0.013	0.35	0.0	0.00	0.0 :
SUB. :	17.68	6.38	0.835	18.47	0.0	0.00	0.0 :	0.45	7.90	0.032	0.71	0.0	0.00	0.0 :
12. :	1.79	11.88	0.276	6.95	18.0	0.16	21.4 :	0.19	11.97	0.029	0.77	2.3	0.12	2.6 :
14. :	1.25	13.96	0.266	7.01	26.2	0.13	30.1 :	0.05	13.60	0.010	0.26	0.8	0.14	1.0 :
SUB. :	3.04	12.74	0.542	13.97	44.2	0.14	51.5 :	0.23	12.30	0.039	1.03	3.1	0.12	3.1 :
16. :	1.14	16.07	0.323	9.30	46.8	0.13	54.0 :	0.07	15.71	0.020	0.57	2.4	0.09	2.6 :
18. :	0.78	18.18	0.282	8.47	48.1	0.10	53.7 :	0.05	17.61	0.018	0.56	2.9	0.09	3.2 :
20. :	1.03	19.50	0.428	12.71	80.4	0.15	94.1 :	0.06	19.59	0.025	0.81	4.9	0.11	5.5 :
22. :	0.08	21.00	0.040	1.08	5.2	0.17	6.3 :	0.08	21.92	0.041	1.21	6.8	0.13	7.8 :
24. :	0.35	23.26	0.205	5.62	45.3	0.13	52.1 :	0.04	23.87	0.024	0.71	4.9	0.10	5.5 :
26. :	0.14	25.40	0.095	2.75	21.2	0.13	24.4 :	0.05	26.08	0.034	0.97	6.3	0.12	7.2 :
28. :	0.03	28.80	0.025	0.69	5.9	0.13	6.8 :	0.15	27.60	0.124	3.81	22.8	0.04	23.7 :
30. :	0.10	30.32	0.097	2.71	23.1	0.13	26.6 :	0.08	29.79	0.080	2.41	16.3	0.13	18.8 :
32. :	0.00	0.00	0.000	0.00	0.0	0.00	0.0 :	0.01	31.48	0.014	0.40	3.3	0.13	3.8 :
34. :	0.00	0.00	0.000	0.00	0.0	0.00	0.0 :	0.01	33.67	0.010	0.28	2.3	0.13	2.6 :
36. :	0.00	0.00	0.000	0.00	0.0	0.00	0.0 :	0.01	35.94	0.007	0.21	1.8	0.13	2.1 :
38. :	0.07	38.20	0.108	3.13	26.7	0.13	30.7 :	0.01	38.00	0.009	0.26	2.1	0.13	2.4 :
40. :	0.00	0.00	0.000	0.00	0.0	0.00	0.0 :	0.01	46.80	0.017	0.48	4.3	0.13	4.9 :
SUB. :	3.71	19.46	1.602	46.46	302.8	0.13	348.5 :	0.62	24.33	0.423	12.69	81.1	0.10	81.1 :
TOTAL:	24.43	9.16	2.979	78.90	347.0	0.13	400.1 :	13.62	3.88	0.587	14.43	84.3	0.10	84.2 :

Table 2—FVS Stand Table—Size Class Arrayed. (WPWP030.PT2)

--- Forest Management Plan Analysis

TABLE 2-1 S T O C K   A N D   S T A N D SUMMARY (PER ACRE)

	FREQ	BASAL AREA	CUBIC FEET	GROSS BOARD MEASURE	% DEF	NET BOARD MEASURE	FREQ	BASAL AREA	CUBIC FEET	GROSS BOARD MEASURE	% DEF	NET BOARD MEASURE
--- Balsam Fir (012)							**--- Black Spruce (095)**					
SAPLINGS 2-4	4.28	0.273	0.00	0.0	0.00	0.0	0.01	0.001	0.00	0.0	0.00	0.0
POLES 6-10	0.02	0.003	0.05	0.0	0.00	0.0	0.00	0.000	0.00	0.0	0.00	0.0
SM. SAW 12-14	0.00	0.000	0.00	0.0	0.03	0.0	0.00	0.000	0.00	0.0	0.00	0.0
LG. SAW 16-40	0.00	0.004	0.11	0.5	0.00	0.5	0.00	0.000	0.00	0.0	0.00	0.0
TOTAL	4.30	0.280	0.17	0.5	0.00	0.5	0.01	0.001	0.00	0.0	0.00	0.0
--- Red Pine (125)							**--- White Pine (129)**					
SAPLINGS 2-4	0.00	0.000	0.00	0.0	0.00	0.0	0.00	0.000	0.00	0.0	0.00	0.0
POLES 6-10	0.00	0.000	0.00	0.0	0.00	0.0	0.55	0.201	4.05	0.0	0.00	0.0
SM. SAW 12-14	0.00	0.000	0.00	0.0	0.00	0.0	0.48	0.453	12.49	51.7	0.13	51.6
LG. SAW 16-40	4.01	8.424	257.22	1706.2	0.12	1704.1	32.91	132.911	3779.87	28857.2	0.13	28818.3
TOTAL	4.01	8.424	257.22	1706.2	0.12	1704.1	33.94	133.565	3796.42	28908.9	0.13	28869.9
--- Northern White-Cedar (241)							**--- Eastern Hemlock (261)**					
SAPLINGS 2-4	0.00	0.000	0.00	0.0	0.00	0.0	3.90	0.220	0.00	0.0	0.00	0.0
POLES 6-10	0.00	0.000	0.00	0.0	0.00	0.0	4.25	0.778	18.05	0.0	0.00	0.0
SM. SAW 12-14	0.00	0.000	0.00	0.0	0.00	0.0	2.45	2.273	52.61	150.2	0.12	150.0
LG. SAW 16-40	0.00	0.000	0.00	0.0	0.00	0.0	2.45	3.602	99.94	396.0	0.09	395.7
TOTAL	0.00	0.000	0.00	0.0	0.00	0.0	13.05	6.873	170.60	546.2	0.10	545.7
--- Soft Maple (316)							**--- Hard Maple (318)**					
SAPLINGS 2-4	14.61	1.148	0.00	0.0	0.00	0.0	56.04	2.946	0.00	0.0	0.00	0.0
POLES 6-10	10.53	4.484	117.03	0.0	0.00	0.0	1.06	0.384	7.11	0.0	0.00	0.0
SM. SAW 12-14	1.94	1.721	46.38	129.8	0.19	129.6	0.36	0.337	9.29	24.5	0.10	24.5
LG. SAW 16-40	2.20	3.916	122.08	529.1	0.08	528.7	1.65	3.413	109.74	517.1	0.08	516.8
TOTAL	29.27	11.269	285.48	658.9	0.10	658.2	59.11	7.079	126.13	541.6	0.08	541.2
--- Yellow Birch (371)							**--- Paper Birch (375)**					
SAPLINGS 2-4	14.60	0.820	0.00	0.0	0.00	0.0	0.33	0.020	0.00	0.0	0.00	0.0
POLES 6-10	0.06	0.008	0.17	0.0	0.00	0.0	1.02	0.360	8.08	0.0	0.00	0.0
SM. SAW 12-14	0.28	0.240	6.55	19.2	0.09	19.2	0.14	0.112	3.12	9.0	0.05	9.0
LG. SAW 16-40	0.08	0.096	2.67	9.8	0.07	9.8	0.09	0.146	4.14	15.9	0.04	15.9
TOTAL	15.01	1.165	9.39	28.9	0.08	28.9	1.57	0.638	15.34	24.9	0.04	24.9

(con.)

Table 2 (Con.)   (WPWP030.PT2)

--- Forest Management Plan Analysis

DATE RUN -   04/08/1997
PLOT ACRES -   26.00
MEASUREMENT LENGTH -   5.00 YEARS

TABLE 2-3 M E A S U R E D   A N N U A L   H A R V E S T SUMMARY (PER ACRE)

		: - - - - - 146- 150 ANNUAL HARVEST - - - - - :						: - - - - - 146- 150 ANNUAL HARVEST - - - - - :				
		: FREQ	BA	CUBIC	GRS BM	%	NET BM:	FREQ	BA	CUBIC	GRS BM	%	NET BM:
		: /AC	/AC/YR	/AC/YR	/AC/YR	DEF	/AC/YR :	/AC	/AC/YR	/AC/YR	/AC/YR	DEF	/AC/YR :
		: --- Balsam Fir (012)						: --- Black Spruce (095)					:
POLES	6-10 :	0.58	0.031	0.61	0.0	0.00	0.0 :	0.00	0.000	0.00	0.0	0.00	0.0 :
SM. SAW	12-14 :	0.00	0.000	0.00	0.0	0.00	0.0 :	0.00	0.000	0.00	0.0	0.00	0.0 :
LG. SAW	16-40 :	0.00	0.000	0.00	0.0	0.00	0.0 :	0.00	0.000	0.00	0.0	0.00	0.0 :
TOTAL	:	0.58	0.031	0.61	0.0	0.00	0.0 :	0.00	0.000	0.00	0.C	0.00	0.0 :
		: --- Red Pine (125)						: --- White Pine (129)					:
POLES	6-10 :	0.00	0.000	0.00	0.0	0.00	0.0 :	0.38	0.012	0.13	0.0	0.00	0.0 :
SM. SAW	12-14 :	0.00	0.000	0.00	0.0	0.00	0.0 :	0.76	0.150	4.27	19.5	0.13	22.3 :
LG. SAW	16-40 :	0.30	0.121	3.52	26.5	0.16	31.4 :	2.28	1.085	30.38	215.6	0.15	253.3 :
TOTAL	:	0.30	0.121	3.52	26.5	0.16	31.4 :	3.42	1.247	34.78	235.1	0.15	275.7 :
		: --- Northern White-Cedar (241)						: --- Eastern Hemlock (261)					:
POLES	6-10 :	0.38	0.018	0.16	0.0	0.00	0.0 :	3.65	0.161	3.27	0.0	0.00	0.0 :
SM. SAW	12-14 :	0.19	0.031	0.57	1.2	0.28	1.6 :	0.58	0.107	2.35	5.7	0.13	6.5 :
LG. SAW	16-40 :	0.00	0.000	0.00	0.0	0.00	0.0 :	0.55	0.200	6.64	36.2	0.04	37.8 :
TOTAL	:	0.57	0.049	0.74	1.2	0.28	1.6 :	4.78	0.468	12.26	41.9	0.05	44.3 :
		: --- Soft Maple (316)						: --- Hard Maple (318)					:
POLES	6-10 :	7.91	0.395	9.22	0.0	0.00	0.0 :	0.19	0.008	0.12	0.0	0.00	0.0 :
SM. SAW	12-14 :	1.21	0.192	5.13	13.0	0.18	15.8 :	0.15	0.031	0.88	2.7	0.10	3.0 :
LG. SAW	16-40 :	0.35	0.116	3.46	13.6	0.11	15.2 :	0.23	0.081	2.47	10.9	0.05	11.5 :
TOTAL	:	9.46	0.703	17.80	26.6	0.14	31.0 :	0.58	0.120	3.46	13.6	0.06	14.5 :
		: --- Yellow Birch (371)						: --- Paper Birch (375)					:
POLES	6-10 :	0.22	0.021	0.44	0.0	0.00	0.0 :	0.96	0.063	1.49	0.0	0.00	0.0 :
SM. SAW	12-14 :	0.15	0.030	0.76	2.1	0.08	2.3 :	0.00	0.000	0.00	0.0	0.00	0.0 :
LG. SAW	16-40 :	0.00	0.000	0.00	0.0	0.00	0.0 :	0.00	0.000	0.00	0.0	0.00	0.0 :
TOTAL	:	0.37	0.051	1.19	2.1	0.08	2.3 :	0.96	0.063	1.49	0.0	0.00	0.0 :
		: --- American Beech (531)						: --- White Ash (541)					:
POLES	6-10 :	2.83	0.091	2.33	0.0	0.00	0.0 :	0.00	0.000	0.00	0.0	0.00	0.0 :
SM. SAW	12-14 :	0.00	0.000	0.00	0.0	0.00	0.0 :	0.00	0.000	0.00	0.0	0.00	0.0 :
LG. SAW	16-40 :	0.00	0.000	0.00	0.0	0.00	0.0 :	0.00	0.000	0.00	0.0	0.00	0.0 :
TOTAL	:	2.83	0.091	2.33	0.0	0.00	0.0 :	0.00	0.000	0.00	0.0	0.00	0.0 :

Table 2 (Con.)   (WPWP030.PT2)

--- Forest Management Plan Analysis

DATE RUN - 04/08/1997
PLOT ACRES - 26.00
MEASUREMENT LENGTH - 5.00 YEARS

TABLE 2-4 M E A S U R E D   A N N U A L   M O R T A L I T Y   SUMMARY (PER ACRE)

		FREQ /AC	BA /AC/YR	CUBIC /AC/YR	GRS BM /AC/YR	% DEF	NET BM /AC/YR	FREQ /AC	BA /AC/YR	CUBIC /AC/YR	GRS BM /AC/YR	% DEF	NET BM /AC/YR
		\-\-\-\-\- 146- 150 ANNUAL MORTALITY \-\-\-\-\-						\-\-\-\-\- 146- 150 ANNUAL MORTALITY \-\-\-\-\-					
		--- Balsam Fir (012)						--- Black Spruce (095)					
POLES	6-10	0.00	0.000	0.00	0.0	0.00	0.0	0.00	0.000	0.00	0.0	0.00	0.0
SM. SAW	12-14	0.00	0.000	0.00	0.0	0.03	0.0	0.00	0.000	0.00	0.0	0.00	0.0
LG. SAW	16-40	0.00	0.001	0.02	0.1	0.00	0.0	0.00	0.000	0.00	0.0	0.00	0.0
TOTAL		0.35	0.006	0.02	0.1	0.00	0.1	0.00	0.000	0.00	0.0	0.00	0.0
		--- Red Pine (125)						--- White Pine (129)					
POLES	6-10	0.00	0.000	0.00	0.0	0.00	0.0	0.05	0.004	0.08	0.0	0.00	0.0
SM. SAW	12-14	0.00	0.000	0.00	0.0	0.00	0.0	0.06	0.010	0.27	1.0	0.12	1.0
LG. SAW	16-40	0.04	0.015	0.48	3.0	0.12	3.0	0.33	0.265	7.69	54.1	0.13	54.1
TOTAL		0.04	0.015	0.48	3.0	0.12	3.0	0.44	0.279	8.04	55.1	0.13	55.1
		--- Northern White-Cedar (241)						--- Eastern Hemlock (261)					
POLES	6-10	0.00	0.000	0.00	0.0	0.00	0.0	0.01	0.001	0.01	0.0	0.00	0.0
SM. SAW	12-14	0.00	0.000	0.00	0.0	0.00	0.0	0.02	0.004	0.11	0.3	0.12	0.3
LG. SAW	16-40	0.00	0.000	0.00	0.0	0.00	0.0	0.01	0.004	0.11	0.4	0.06	0.4
TOTAL		0.00	0.000	0.00	0.0	0.00	0.0	0.36	0.013	0.23	0.8	0.09	0.8
		--- Soft Maple (316)						--- Hard Maple (318)					
POLES	6-10	0.09	0.007	0.13	0.0	0.00	0.0	0.04	0.002	0.04	0.0	0.00	0.0
SM. SAW	12-14	0.06	0.010	0.27	0.8	0.18	0.8	0.01	0.002	0.04	0.1	0.10	0.1
LG. SAW	16-40	0.04	0.014	0.45	1.9	0.08	1.9	0.02	0.006	0.21	1.0	0.07	1.0
TOTAL		2.24	0.046	0.85	2.7	0.11	2.7	4.77	0.049	0.29	1.1	0.07	1.1
		--- Yellow Birch (371)						--- Paper Birch (375)					
POLES	6-10	0.00	0.000	0.00	0.0	0.00	0.0	0.06	0.004	0.10	0.0	0.00	0.0
SM. SAW	12-14	0.03	0.005	0:13	0.4	0.09	0.4	0.01	0.001	0.03	0.1	0.05	0.1
LG. SAW	16-40	0.01	0.002	0.06	0.2	0.07	0.2	0.00	0.001	0.03	0.1	0.04	0.1
TOTAL		1.04	0.016	0.19	0.6	0.08	0.6	0.08	0.006	0.16	0.2	0.04	0.2
		--- American Beech (531)						--- White Ash (541)					
POLES	6-10	0.00	0.000	0.00	0.0	0.00	0.0	0.02	0.001	0.02	0.0	0.00	0.0
SM. SAW	12-14	0.01	0.003	0.06	0.2	0.20	0.2	0.00	0.000	0.00	0.0	0.00	0.0
LG. SAW	16-40	0.01	0.003	0.08	0.4	0.10	0.4	0.00	0.000	0.00	0.0	0.00	0.0
TOTAL		3.63	0.024	0.15	0.6	0.13	0.6	0.12	0.002	0.02	0.0	0.00	0.0

Table 3—Time Basis Yield Report.

Hemlock - Sugar Maple Cover Type - All-Aged Selection (20 CFI Plots)

Entry Interval	YEAR	STOCKING					HARVEST					MORTALITY					Plot Count
		TPA	DBH	BA	CU	BD	TPA	DBH	BA	CU	BD	TPA	DBH	BA	CU	BD	
	1988	391	5.6	133	3437	13992	0	0.0	0	0	0	0	0.0	0	0	0	20
	1993	353	5.8	118	2964	10750	19	17.3	35	1036	4806	18	3.0	2	37	148	20
1	1998	433	5.2	136	3522	12476	0	0.0	0	0	0	17	3.5	2	49	184	20
	2003	408	5.8	149	3936	13863	0	16.0	0	0	0	25	3.2	3	73	279	20
	2008	349	5.5	113	3024	10296	42	13.7	48	1311	4451	18	2.8	2	47	183	20
2	2013	421	4.9	126	3359	11225	0	0.0	0	0	0	24	2.6	2	58	220	20
	2018	393	5.5	137	3743	12354	0	0.0	0	0	0	28	2.5	3	77	295	20
	2023	331	5.3	111	3053	11035	45	11.8	38	1052	2258	17	2.7	2	55	237	20
3	2028	406	4.7	122	3377	12713	0	0.0	0	0	0	23	2.5	2	59	243	20
	2033	378	5.3	133	3708	13732	0	0.0	0	0	0	28	2.4	3	82	362	20
	2038	336	5.3	116	3217	11470	24	13.9	28	805	2928	19	2.7	2	66	297	20
4	2043	405	4.5	122	3366	12018	0	0.0	0	0	0	27	3.4	5	131	384	20
	2048	378	5.1	131	3666	13053	0	0.0	0	0	0	27	2.4	3	88	400	20
	2053	327	5.0	109	3053	11819	33	12.4	31	920	2229	18	2.8	3.	73	335	20
5	2058	401	4.4	118	3320	12634	0	0.0	0	0	0	23	2.6	3	80	348	20
	2063	374	5.0	129	3657	13639	0	0.0	0	0	0	26	2.4	3	90	403	20
	2068	335	5.0	113	3185	12186	20	14.0	24	721	2392	19	2.8	3	75	322	20
6	2073	407	4.4	122	3433	12901	0	0.0	0	0	0	25	2.6	3	87	374	20
	2078	379	4.9	130	3679	14267	0	0.0	0	0	0	28	2.6	4	105	434	20
	2083	335	4.8	106	2977	11906	25	14.3	32	947	3101	18	2.7	3	74	355	20
7	2088	410	4.2	115	3234	12503	0	0.0	0	0	0	23	2.6	3	84	398	20
	2093	383	4.8	124	3542	13491	0	0.0	0	0	0	27	2.4	3	93	435	20
	2098	347	4.9	108	3055	11543	17	15.4	26	776	2995	19	2.7	3	78	357	20
8	2103	420	4.3	118	3368	12543	0	0.0	0	0	0	24	2.6	3	83	382	20
	2108	392	5.0	129	3697	13537	0	0.0	0	0	0	28	2.4	4	100	456	20
	2113	347	4.9	108	3075	11467	26	14.0	31	959	3444	19	2.5	3	70	336	20
9	2118	420	4.4	120	3410	12810	0	0.0	0	0	0	24	2.5	3	83	386	20
	2123	393	5.0	131	3759	13097	0	0.0	0	0	0	28	2.3	3	88	396	20
	2128	348	4.9	107	3017	11206	27	14.6	35	1088	3733	18	2.6	2	66	308	20
10	2133	422	4.4	119	3402	12396	0	0.0	0	0	0	23	2.5	3	73	336	20
	2138	396	5.0	131	3774	13387	0	0.0	0	0	0	27	2.3	3	85	370	20
	2143	354	4.9	107	3049	10984	23	16.1	35	1101	4266	19	2.5	2	60	272	20

Table 4—Age Basis Yield Report.

White Pine Cover Type - Shelterwood (27 CFI Plots)

Stand Origin	AGE	STOCKING					HARVEST					MORTALITY					Plot Count
		TPA	DBH	BA/AC	CU/AC	BD/AC	TPA	DBH	BA/AC	CU/AC	BD/AC	TPA	DBH	BA/AC	CU/AC	BD/AC	
	53	880	4	152	3079	6943	79	7	20	279	0	15	7	4	70	75	2
	58	779	4	149	3084	8297	30	9	14	232	204	71	3	5	74	109	2
	62	551	5	151	3152	9193	0	0	0	0	0	36	3	4	58	125	3
	67	533	6	167	3717	11461	11	8	4	83	58	28	4	4	53	144	4
	72	475	6	163	3708	12491	41	8	15	308	493	26	4	5	98	294	4
	77	420	6	158	3662	13301	17	7	5	119	79	20	5	4	83	266	5
	82	394	7	164	3922	14952	10	10	5	91	60	24	4	5	104	400	5
	87	365	7	171	4152	16925	5	10	3	64	124	23	4	4	92	360	5
	92	323	8	173	4263	18400	26	7	8	182	339	22	5	4	89	360	5
Exist.	97	568	5	185	4522	20445	4	12	3	67	165	15	5	4	76	322	6
	102	459	6	178	4495	21748	27	9	13	295	593	87	3	6	87	397	6
	107	463	6	187	4828	26688	3	14	3	74	260	41	3	4	79	377	8
	112	345	7	184	4829	28164	12	13	12	357	1559	87	3	6	112	628	9
	117	276	7	175	4691	28380	15	10	9	224	662	35	3	5	99	564	11
	122	234	8	176	4743	28985	13	8	6	155	733	24	4	4	86	469	12
	127	249	8	174	4700	28875	7	10	4	99	360	12	4	2	53	249	19
	132	241	8	178	4822	30914	33	7	12	283	873	15	3	2	46	230	23
	137	201	9	174	4782	31689	20	10	14	363	1507	17	3	2	50	271	24
	142	235	8	182	4945	33331	7	13	9	231	1247	11	4	2	57	338	26
	147	196	9	179	4929	33804	24	9	15	395	1735	14	4	3	72	421	26
	150+/0	204	9	179	4925	33886	3	19	8	220	1465	12	5	6	168	1035	27
	5	829	1	104	2997	22532	175	6	79	2056	12622	1	25	2	69	424	27
	10	784	1	42	1138	9186	21	23	64	1863	13411	24	0	1	42	334	27
	15	723	2	48	1139	9243	0	0	0	0	0	79	1	2	42	327	27
	20	698	2	56	1150	9345	0	0	0	0	0	25	1	1	36	258	27
	25	715	3	67	1168	9423	0	0	0	0	0	15	2	2	41	316	27
	30	698	4	52	170	10	7	31	41	1162	9423	9	2	0	0	0	27
	35	764	4	83	720	37	0	0	0	0	0	10	3	1	1	0	27
	40	716	5	109	1651	42	18	5	3	64	14	31	3	1	5	0	27
	45	700	6	133	2498	191	40	5	6	133	1	20	3	2	12	1	27
	50	576	6	140	2902	739	98	6	21	453	87	26	3	2	15	0	27
	55	454	7	137	3048	2052	128	6	28	594	0	16	3	1	18	5	27
	60	344	8	136	3204	3872	92	7	24	525	123	18	3	1	18	11	27
	65	316	8	142	3461	6793	58	7	18	417	63	11	4	1	18	22	27
Regen. 1	70	258	9	146	3683	11040	44	8	18	431	701	14	3	1	20	35	27
	75	255	9	151	3902	14187	27	10	15	391	879	9	4	1	19	56	27
	80	220	10	155	4074	16528	25	10	16	417	1119	10	4	1	22	70	27
	85	227	9	159	4232	18662	19	12	16	429	1615	7	4	1	26	99	27
	90	197	10	160	4340	20383	19	12	17	457	1902	11	3	1	24	103	27
	95	200	10	162	4432	21846	15	13	16	438	1945	8	4	1	24	105	27
	100	172	11	165	4570	23576	15	12	15	428	1981	9	3	1	23	111	26
	105	177	10	165	4615	24174	14	12	15	414	1979	7	4	1	24	117	25
	110	153	11	165	4669	25732	13	12	14	401	1982	11	3	1	24	128	25
	115	154	11	168	4782	27406	10	12	12	339	1774	7	4	1	25	135	24
	120	134	11	170	4899	29138	10	12	12	341	1811	8	3	1	25	143	23
	125	140	11	170	4945	30047	9	13	12	350	1975	6	4	1	25	150	23
	130	123	12	170	4990	30922	10	12	12	342	1914	6	4	1	26	155	22
	135	125	11	171	5035	31698	8	12	10	301	1763	5	4	1	26	161	22
	140	112	12	169	5022	32071	8	12	11	321	1874	5	4	1	26	164	22
	145	112	12	171	5078	32727	6	12	8	239	1441	4	4	1	27	170	22
	150	101	13	171	5109	33265	7	11	8	244	1438	4	4	1	28	176	21
	150+/0	91	14	172	5189	34043	6	11	7	195	1179	4	5	1	27	176	21
	5	821	1	105	3252	21560	71	9	72	2101	13657	0	29	1	18	119	19
	10	786	1	41	1209	7997	13	30	65	2013	13348	21	1	2	70	458	18
	15	728	2	45	1128	7486	0	0	0	0	0	77	1	4	105	680	16
	20	711	2	51	1070	7115	0	0	0	0	0	18	2	3	93	613	15
Regen. 2	25	742	3	65	1011	6356	0	0	0	0	0	12	3	3	96	640	8
	30	724	4	71	600	139	6	28	28	866	5712	12	2	0	1	0	4
	35	803	5	121	1755	650	0	0	0	0	0	14	3	1	7	4	3
	40	661	6	147	2653	0	95	6	21	425	379	44	3	2	9	0	1

Using the Stand Visualization System as a Communication Tool: Examples from the Pacific Southwest Region

F. Michael Landram

Abstract—Employees of the Pacific Southwest Region have been using the Stand Visualization System as a communication tool since early 1996. Stand structure-fire hazard relationships, spatial variation of trees, before and after treatment comparisons, and change through time have all been communicated with the tool. It receives the most use by individuals or small teams, the least use at public meetings. Its effectiveness as a communications tool is largely dependent on speaker-audience dynamics, believability of the graphics, and ease of use of the system.

In January 1994 I was among those calling for the Forest Vegetation Simulator (FVS) (Teck and others 1996) to be more visual for communication purposes. By 1996, the Stand Visualization System (McGaughey 1997) was linked to FVS; the Pacific Southwest Region of the U.S. Department of Agriculture, Forest Service began using it. This paper describes its use as a communication tool through January 1997.

Examples

The Stand Vegetation System (SVS) has been used in the Pacific Southwest Region to communicate fire hazard-stand structure relationships, spatial variation, treatment comparisons, and stand development.

Anecdotal evidence in California of altered wildfire behavior as a result of stand structure was summarized in 1996 (Landram 1996). SVS was used to help communicate findings (fig. 1, 2). The Sierra Nevada Ecosystem Project, concluded in 1996, included work on the relationship between silviculture and fuels (Weatherspoon 1996). FVS was used to help communicate this information at professional meetings (fig. 3, 4).

During work on the California Spotted Owl EIS, SVS was used to communicate within stand spatial variation (fig. 5), visual differences between silvicultural treatments (fig. 6, 7), and projected change through time (fig. 8-10).
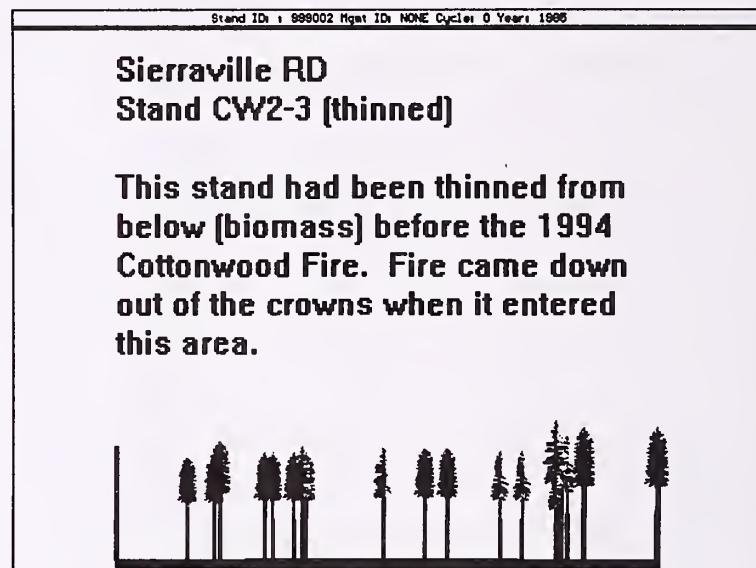

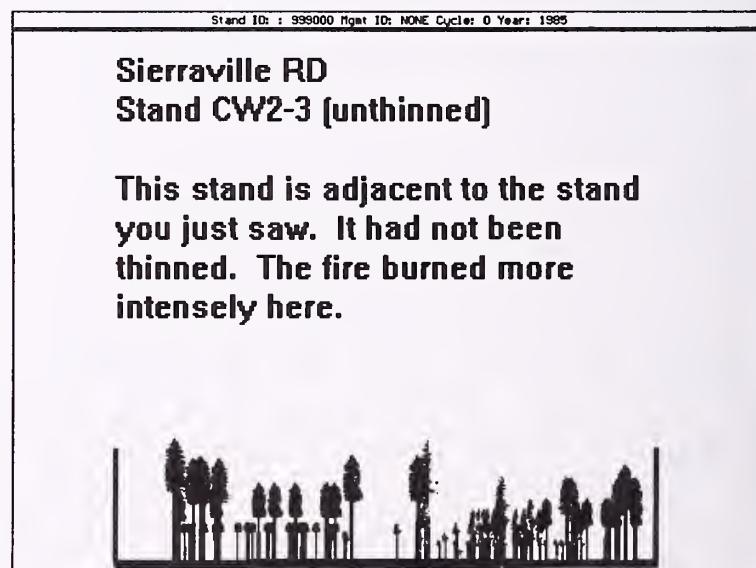**Figure 1**—A profile view from SVS showing height to first live limb and crown spacing.

Figure 2—A profile view from SVS showing lower height to first live limb and closer crown spacing.

Removal of understory;
No treatment of surface fuels
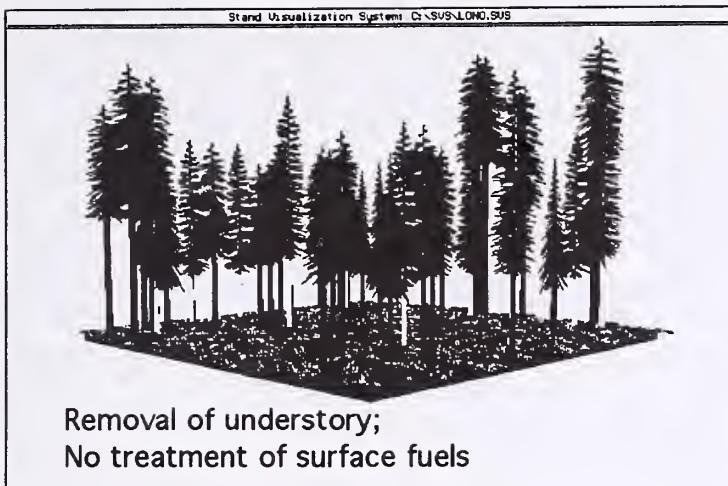
Figure 3—A perspective view from SVS show-
ing surface fuels created by thinning from below.

Removal of overstory;
No treatment of surface fuels

Figure 4—A perspective view from SVS
showing surface fuels created by thinning
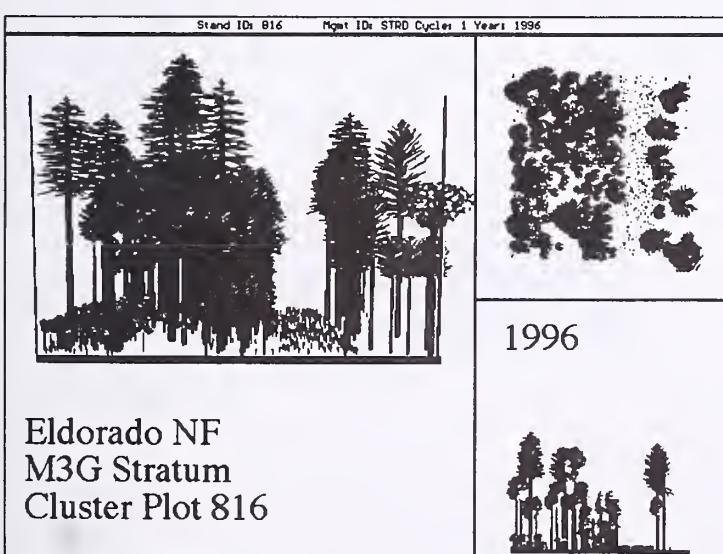from above.

Eldorado NF
M3G Stratum
Cluster Plot 816

1996

Figure 5—These views use the SVS feature that
allows for tracking of tree location by plot.

Eldorado NF   2006
M3G Stratum
Cluster Plot 816   submerchantable thin

Figure 6—One thinning prescription.

Eldorado NF   2006
M3G Stratum
Cluster Plot 816   heavy thin from below

Figure 7—A different thinning prescription.

Eldorado NF   2006
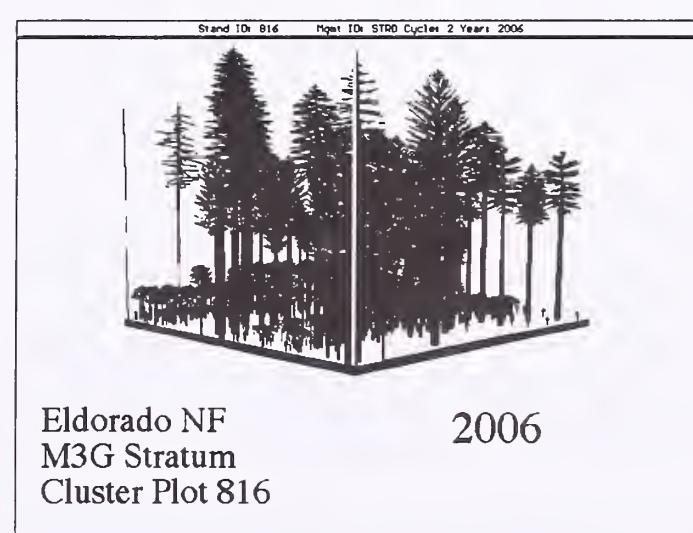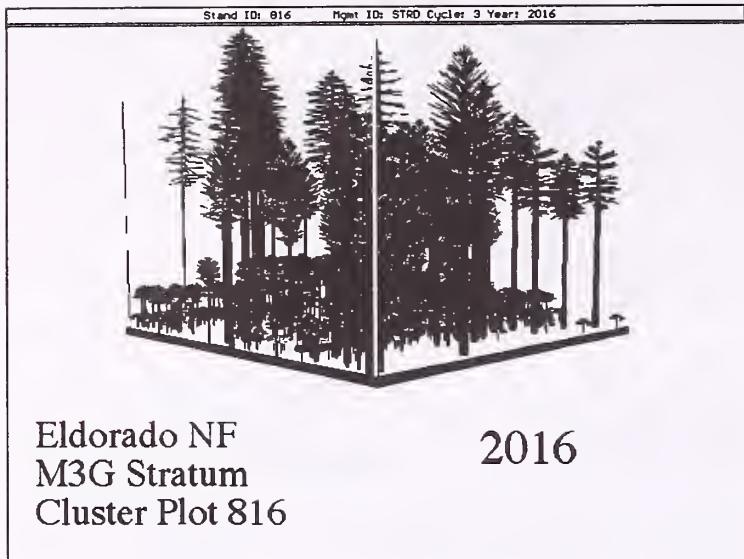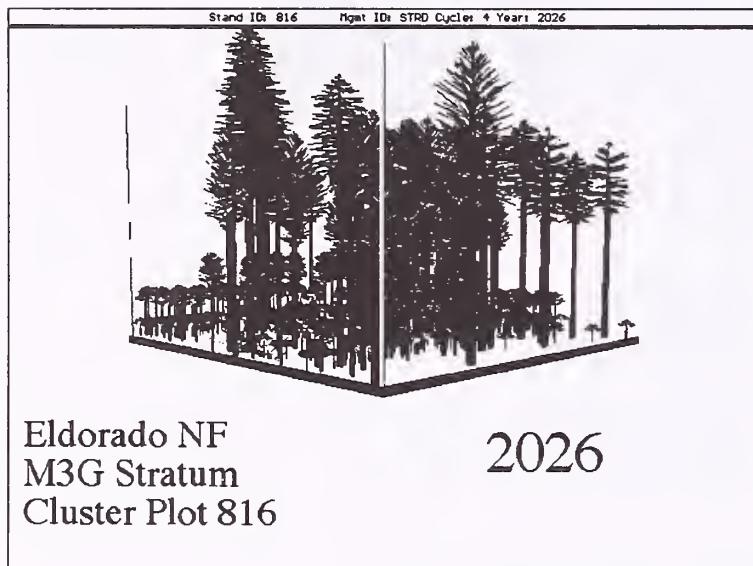M3G Stratum
Cluster Plot 816

Figure 8—An SVS perspective view of a pro-
jected stand in the year 2006.

Figure 9—The same stand depicted in figure 8 in the year 2016.

Figure 10—The same stand depicted in figure 9 in the year 2026.

Extent of Experience

Through January 1997, about 100 people had been trained in use of the Stand Visualization System. Its use by individuals to visualize existing and future stand conditions during the preparation of treatment prescriptions is common. Its use by interdisciplinary teams to develop treatment proposals is occasional. Its use at public meetings is rare. Why?

## Effectiveness as a Communication Tool

The effectiveness of SVS as a communication tool is affected by the individuals using it, by the apparent accuracy of the graphics, and by its ease of use.

The subject knowledge, interest level, and personal agenda of both the speaker and audience have a profound affect on communication in general. Resource professionals familiar with stand inventory and summarization techniques that usually display tables of numbers do not necessarily experience increased awareness using SVS because they are already involved in a greater level of detail than can be displayed by the tool. Those with lesser familiarity, however, find it much easier to relate the visualizations to their own experience with the forest, which in turn increases understanding and ability to formulate questions. Communication can be greatly enhanced as a result.
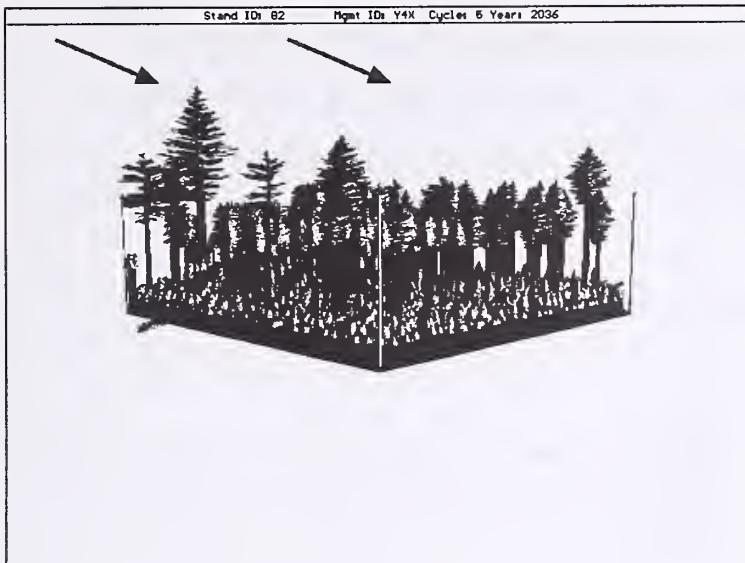
Optimum use of the tool is dependent on how believable the graphics are. Perceived errors in the graphics are a barrier to effective communication. Figure 11 displays
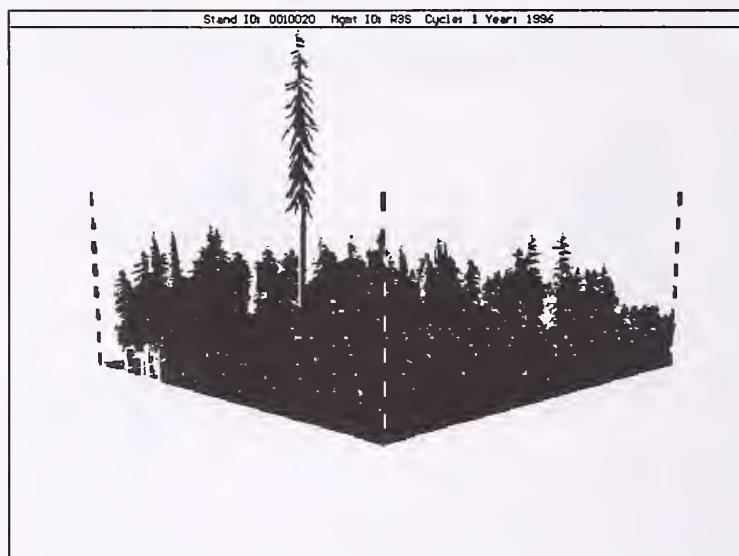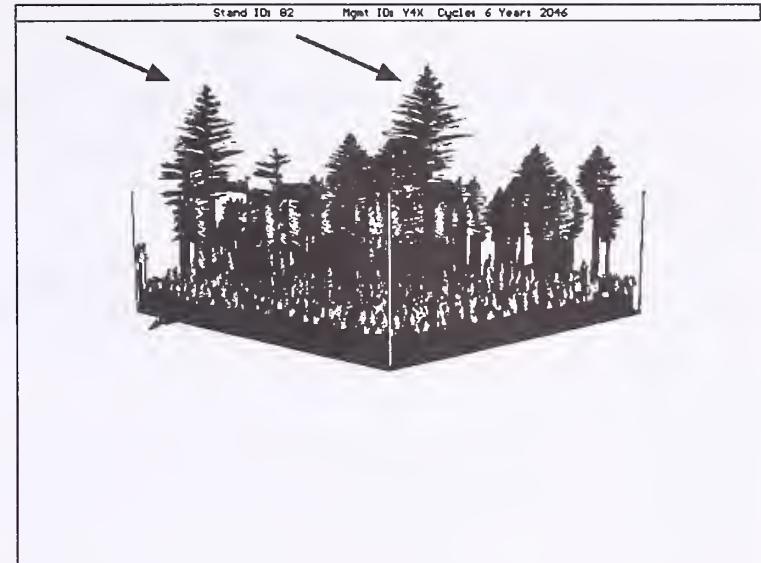

Figure 11—A height data error for one tree is apparent.
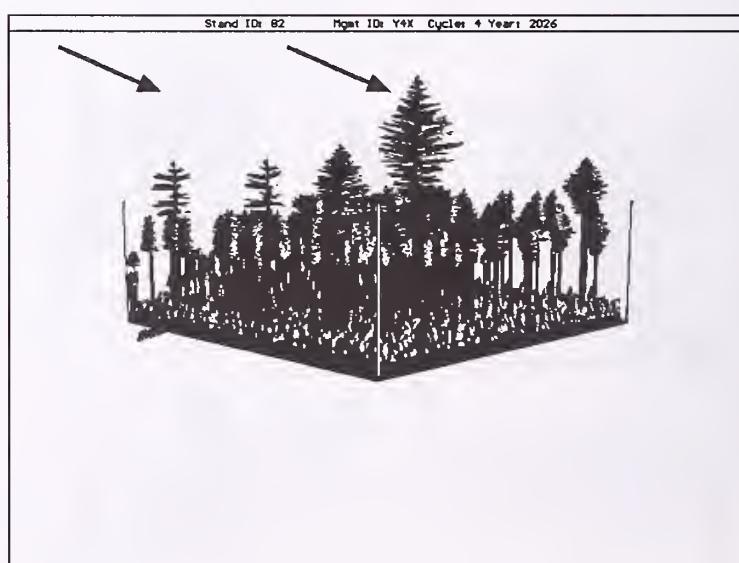
Figure 12—Notice the fate of the large trees in the next two figures as the stand grows. This figure depicts the beginning of a projection.

Figure 13—Large trees have disappeared in places and appeared in other places.

Figure 14—The large trees are back in this last year. No treatments were simulated in this projection.

inventory data that contained a height error for one tree. Conversation about stand structure is inhibited until the error can be corrected. Figures 12 to 14 display a growing stand. Notice how some larger trees "disappear" in the second period only to "reappear" in the next. This "apparent error" is caused by tree records that represent less than one tree per acre being sorted for display differently in each period. The statistical accuracy of the presentation is maintained, but stand growth does not appear "real" and conversation becomes absorbed with explaining why.

Initial attraction to the tool becomes tempered by the time it takes to master it. As ease of use improves, so will the quantity of use, and its likely effectiveness in communication will increase. Enhancements are ongoing and many will be in place by the time you read this.

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Current Vegetation Survey in the Pacific Northwest Region: A Direct Link to FVS and the Insect and Disease Extensions

Tommy F. Gregg
Ellen Michaels Goheen

Abstract—The U.S. Forest Service's Pacific Northwest Region's new Current Vegetation Survey was designed with multidisciplinary input into design, data elements, and outputs. Insect and disease information is collected based on damaging agent priority and according to Forest Vegetation Simulator insect and disease model extension data needs. Available output tables include detailed insect and disease information and model-ready keyword sets describing current plot-level impacts, as well as FVS-ready treelist files, tables describing down wood and standing dead trees, and CVS images of plot conditions. Challenges associated with insect and disease data collection and preliminary analysis of one National Forest's insect and disease information are presented.

Project History

The Pacific Northwest Region's development of a new Region-wide vegetation inventory provided opportunities for multidisciplinary input into inventory plot design, data elements, and data outputs (Max and others 1996). Forest Insect and Disease staff were particularly interested in providing input because we wanted to ensure that insect and disease considerations were adequately addressed during the next round of National Forest planning. We wanted insect and disease data gathered in such a way that they could be directly entered into recently developed insect and disease extensions to the Forest Vegetation Simulator (FVS). We also had concerns about the quality and quantity of insect and disease information gathered in previous Region-wide inventories and were hoping to influence the inventory process at levels including data element design, prioritization, and contract administration and inspection.

Okanogan Pilot Project

We completed a pilot study on the Okanogan National Forest in 1992. Objectives of the study included testing insect and disease data-gathering procedures to understand what to expect from field inventory crews who were not insect and disease specialists, adjusting detail and coding to have the information model-ready, and putting our information in the context of other resource information needs. An initial list of data elements and a preliminary plot design was developed. Field crews gathered data across a range of forest types on the Forest. At intervals during the summer, forest inventory, silviculture, ecology, wildlife biology, fuels, and insect and disease specialists gathered to discuss efficiency of data collection, problems encountered by the crews in interpreting instructions, and the pros and cons of tested procedures. Changes were made and evaluation continued for 4 months. The list of data elements agreed to during the Okanogan Pilot study became the core data elements for the Current Vegetation Survey (CVS).

Based on our pilot study experience we developed a set of recommendations pertaining to gathering the insect and disease data. These included:

- Providing the opportunity to collect information on up to three insect, disease, or damages encountered on a given tree.
- Developing priorities within the insect and disease category to ensure that the most important diseases and insects were catalogued first.
- Improving the contract specifications, including providing incentives for greater detail of disease and insect information.
- Increasing the insect and disease awareness of contract inspectors through training, written material, and field visits.
- Increasing the insect and disease awareness of inventory contractors through orientations, written materials, and field visits.
- Clearly portraying the insect and disease information gathered on a given plot via detailed tables .
- Describing the incidence and severity of insects and diseases via keywords associated with insect and disease model extensions to FVS and incorporating the insect and disease keywords directly into plot design and description keyword sets.

The Current Vegetation Survey

The first plots for the Current Vegetation Survey (CVS) were installed in the summer of 1993. This permanent plot grid system samples the range of vegetative conditions across all National Forest lands in the Pacific Northwest Region. CVS plots have been established on a 3.4 mile grid across all National Forest lands and on a 1.7 mile grid on all
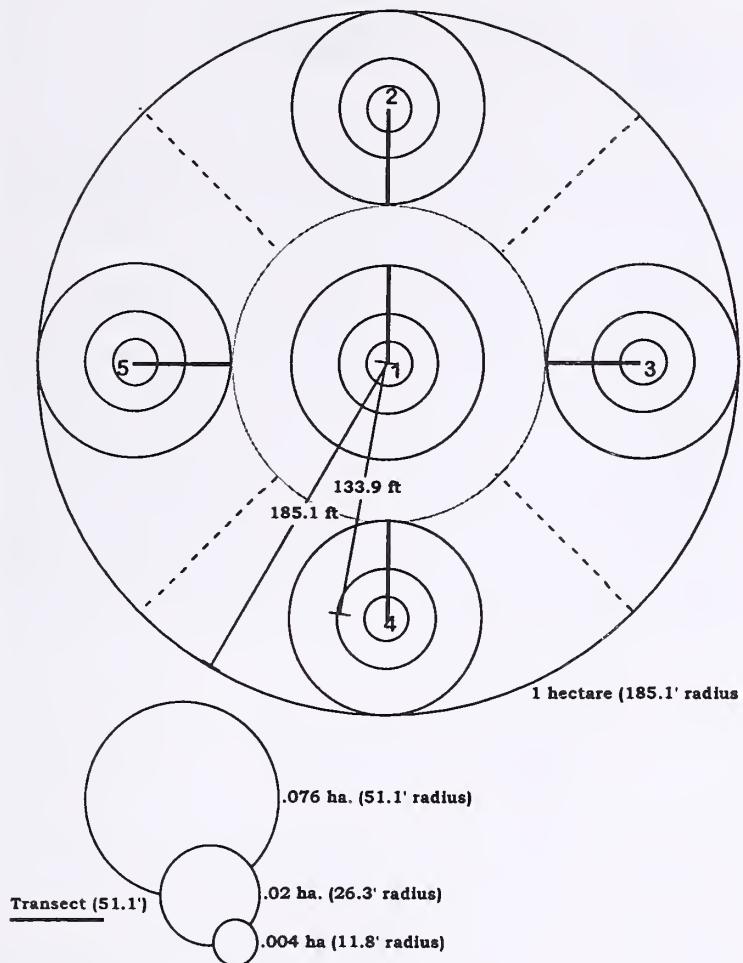
Figure 1—CVS sample unit design.

nondesignated National Forest lands. Remeasurement of a proportion of the plots begins in 1997.

The Sample Unit encompasses 1 ha (2.5 acres) and uses a cluster of subplots of various sizes to sample existing vegetation (fig. 1). Information on deciduous and coniferous trees and shrubs is gathered on subplots. Growth sample trees have height, age, and radial or height growth recorded. Data on standing dead trees are gathered according to tree size; decay classes and wildlife use are described. Indicator shrubs, forbs, and grasses are listed and used to determine subplot-level Plant Associations. Herbacious and graminoid cover is estimated. Down-woody material information is gathered on five transects.

Insect and Disease Information

Insect and disease information collected on each sample unit includes an assessment of root disease severity at each of the five 0.02 hectare ($\frac{1}{20}$th acre) subplots using a 0 to 9 rating scale (Hagle 1985), individual tree-level insect, disease, or physical injury damage and severity assessments, and a tally of stumps with root disease by species and size class.

Emphasis is placed on coding observable insects, pathogens, or damage according to priority. Priority is given to bark beetles, defoliating insects, dwarf mistletoes, root diseases, and topkill or topbreak above other agents or damage categories. More generalized coding by agent group is allowed (for example, bark beetles, root diseases, cankers, and so forth) although contractors are encouraged to identify specific agents whenever possible. Severity is assessed by noting observable characteristics such as proportion of crown affected, or injury to main stem rather than relating damage to volume loss. Up to three agents can be used to describe the damage on an individual tree. "Cause of death," collected during previous inventories, has been replaced by a list of observable insects, pathogens, or injury to better reflect multi-agent interactions and eliminate subjectivity.

Since 1993, much emphasis has been placed on increasing the insect and disease awareness of both inventory contractors and contract inspectors. Formal field training sessions and orientations are held throughout the Region. Follow-up sessions have occurred on some Forests throughout the field season. All crews are provided with field guides and other literature helpful for identifying insect and disease damage. An effort is made to inform data collectors about why certain kinds of data are needed and how the information will be used. Visits are made to specific plots to answer questions pertaining to proper coding and grading when requested. Entomologists and pathologists have been asked to help resolve formal conflicts between contractors and inspectors.

Data Collection Challenges

Even with a fairly rigorous approach to training, orientation, and consultation, misidentification of insects, pathogens, or their damage does occur during the data collection process. Root diseases and bark beetles cause the greatest amount of confusion for both contractors and inspectors; miscalls in these groups cause the greatest number of contractor errors, with root diseases leading the way. Regionally, Armillaria root disease seems to challenge the data collectors the most; they must distinguish between tree-killing *Armillaria ostoyae* and secondary/saprophytic *Armillaria* spp. associated with suppression mortality. A great deal of effort has been spent in the field to provide examples and guidelines. Distinguishing between laminating decays caused by *Heterobasidion annosum* and *Phellinus weirii* also seems to be a problem, particularly on white and grand firs and mountain hemlock.

Crews have also had difficulty identifying stumps with root disease. Much of this error is due to missing the stumps themselves; additional error comes from the confusion associated with other fungi that inhabit stumps.

Errors related to bark beetles include difficulty identifying the year of attack; severity codes for bark beetles include categories such as successful current attack, last year's attack, and older dead. There also seems to be some difficulty distinguishing pitch streams or tubes related to bark beetles and pitch streaming associated with other causes.

Even with multiyear contracts, the beginning of the field season brings the most questions related to identification and coding. Depending on the contractor, there can be a large crew turnover, but most often crews feel more confident after refresher training and orientation. As the spring and summer progress, questions become less frequent, are more sophisticated, and relate to subtle differences in the forest ecosystems being sampled.

Data Outputs

Plot data can be processed into a series of output tables and files using a program written by Tom Gregg. These output tables include: (1) stand tables by species and 2 inch diameter classes for trees per acre (fig. 2) and basal area per acre, (2) trees per acre and basal area per acre by species, by damage codes (fig. 3), (3) 2 inch diameter class breakdown by damage code, (4) dwarf mistletoe severity by host, by 2 inch diameter classes (fig. 4), (5) standing dead trees by snag category (fig. 5), (6) down-woody material reported as pieces per acre and tons per acre (fig. 6), (7) an FVS-ready tree list, (8) an FVS keyword set that includes initial conditions for those insects and diseases present on the plot that have FVS-Insect and Disease Model extensions available (fig. 7), and (9) an SVS image of the circular plot with trees distributed according to their subplot (fig.8).

Results from One National Forest

Insect and disease data from 3.4 mile grid plots on the Winema National Forest, located on the east slope of the Cascade Mountains in southern Oregon, has been looked at in this preliminary analysis.

A standardized (Regional CVS process) Accuracy Assessment was completed on the 3.4 mile grid plots. It showed that for 163 plots assessed, inspector data and contractor data agreed 98 percent of the time for plot-level Root Disease Severity Ratings, with a confidence interval (CI) between 97 percent and 100 percent. This high level of accuracy is probably related to the fact that root disease itself only occurs on 27 percent of plots on this grid; therefore, many plots have ratings of zero. Individual tree damage code assessments were in agreement 93 percent of the time

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         ***  C U R R E N T   V E G E T A T I O N   S U R V E Y  ***

WINEMA N.F.                                         SAMPLE NO. = 1032148
KLAMATH R.D.                                        SURVEY DATE: 09/10/93

                      ( T R E E S / A C R E )
        ==================================================
         DBH   PICO   PIMO   ABMAS   TSME   TOTAL
        --------------------------------------------------
          <1     .0     .0   378.4  199.2   577.6
           2     .0   19.9   139.4  119.5   278.8
           4    4.0    4.0    68.2   40.1   116.3
           6   12.0     .0    44.1   24.1    80.2
           8   24.1     .0    36.1   32.1    92.2
          10   12.0     .0    12.0   16.0    40.1
          12    8.0     .0     8.0    8.0    24.1
          14   10.6     .0     8.5    4.2    23.4
          16    3.2     .0     6.4    6.4    15.9
          18    1.1     .0     2.1    1.1     4.2
          20     .0     .0     1.1     .0     1.1
          22     .0     .0     4.2     .0     4.2
          24     .0     .0     1.1    1.1     2.1
          26     .0     .0     1.1     .0     1.1
          28     .0     .0      .0     .0      .0
          30     .0     .0      .0     .0      .0
          32     .0     .0      .4    1.1     1.5
          34     .0     .0     1.2     .0     1.2
          36     .0     .0      .0     .0      .0
        --------------------------------------------------
          TA    75.0   23.9   712.2  452.7 1263.9
          TA%    5.9    1.9    56.4   35.8   100.0
          SE    41.3   19.3   136.5  120.1   245.5
          CV%  123.1  180.5    42.9   59.3    43.4

          QMD   10.1    2.1     7.2    6.6     7.3

       SAMPLS     5      5       5      5       5
       P(HAT)  1.00    .40    1.00   1.00    1.00
        --------------------------------------------------

       P(HAT) = Proportion of samples with attribute.

       List of Tree Species in Stand Tables:
       =================================================================
         PICO     Lodgepole pine              PIMO     Western white pine
         ABMAS    Shasta red fir              TSME     Mountain hemlock
       -----------------------------------------------------------------
```

Figure 2—Stand table output of trees per acre by 2 inch size classes for one CVS plot.

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            *** C U R R E N T   V E G E T A T I O N   S U R V E Y ***

    WINEMA N.F.                             SAMPLE NO. = 1032148
    KLAMATH R.D.                            SURVEY DATE: 09/10/93
```

S T E M C A N K E R S		PICO	ABMAS	TSME	TOTAL
General Stem/Branch canker GeRC	TA	.0	36.2	.0	36.2
	BA	.0	12.4	.0	12.4

S T E M D E C A Y S		PICO	ABMAS	TSME	TOTAL
General/other stem decays GeSD	TA	13.1	12.3	.0	25.4
	BA	5.9	9.2	.0	15.0
Indian paint fungus ECTI	TA	.0	1.1	.0	1.1
	BA	.0	5.1	.0	5.1
Foliar pathogens General GeFD	TA	.0	32.9	1.1	33.9
	BA	.0	13.7	1.2	15.0

R O O T D I S E A S E S		PICO	ABMAS	TSME	TOTAL
Gen./Other root disease GeRD	TA	.0	3.2	.0	3.2
	BA	.0	.0	.0	.0
Armillaria root disease AROS	TA	.0	9.1	.0	9.1
	BA	.0	9.2	.0	9.2

B A R K B E E T L E S		PICO	ABMAS	TSME	TOTAL
Bark beetle (General/oth) GeBB	TA	46.5	.0	.0	46.5
	BA	24.0	.0	.0	24.0
Fir engraver beetle SCVE	TA	4.0	77.3	.0	81.3
	BA	.7	44.2	.0	44.9

M I S T L E T O E		PICO	ABMAS	TSME	TOTAL
Dwarf mistletoe ARsp	TA	4.2	5.5	9.1	18.8
	BA	5.2	4.6	8.9	18.8

Figure 3—Detailed insect and disease table showing tree per acre and basal area impacts for one CVS plot.

(CI = 90-98) for 2,350 trees. Stumps with root disease presented the greatest insect/disease-related accuracy loss, stump tallies agreed only 66 percent of the time (CI = 45-88), and identification of root disease agreed 72 percent of the time (CI = 52-93). Some changes have been made over the last 3 years to decrease the chances of missing stumps. Assistance in identifying root diseases in stumps will have to continue.

Root disease was found on 26.6 percent of all 3.4 mile grid plots on the Forest. Eighty-three percent of 24 plots on the Klamath Ranger District, 17 percent of 54 plots on the Chemult Ranger District, and 13 percent of 61 plots on the Chiloquin Ranger District were identified as having some level of root disease. A breakdown using Root Disease

Severity Rating indicates that most plots fell into the low impact category. It was possible to look at most of the 1.7 mile grid plots in addition to the 3.4 mile grid plots for root disease severity. In general the proportions of plots with root disease remained very similar for each Ranger District. Areas of the Forest with root disease that were not identified with only the 3.4 mile grid were picked up with the higher resolution sampling.

Dwarf mistletoe is extremely common on the Forest. Sixty-seven percent of all 3.4 mile grid plots had at least one tree with dwarf mistletoe. Seventy percent of the plots on the Chemult Ranger District, 59 percent of the plots on the Chiloquin Ranger District, and 75 percent of the plots on the Klamath Ranger District had dwarf mistletoe recorded.

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          *** C U R R E N T   V E G E T A T I O N   S U R V E Y ***

WINEMA N.F.                                    SAMPLE NO. = 1032148
KLAMATH R.D.                .                  SURVEY DATE: 09/10/93

DISTRIBUTION OF DWARF MISTLETOE BY DMR, HOST AND DIAMETER CLASS
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DIAM. CLASS	Mountain hemlock				Lodgepole pine				Shasta red fir			
	DMR (1-2)	DMR (3-4)	DMR (5-6)	DEAD w/DMT	DMR (1-2)	DMR (3-4)	DMR (5-6)	DEAD w/DMT	DMR (1-2)	DMR (3-4)	DMR (5-6)	DEAD w/DMT
<1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
2	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
4	4.0	.0	.0	.0	.0	.0	.0	.0	4.0	.0	.0	.0
6	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
8	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
10	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
12	.0	4.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
14	.0	.0	.0	.0	2.1	.0	.0	1.1	.0	.0	.0	.0
16	.0	.0	.0	.0	1.1	.0	.0	.0	.0	.0	.0	.0
18	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.1	.0	.0
20	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
22	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
24	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
26	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
28	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
30	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
32	1.1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
34	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.4	.0
36	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
TOTAL	5.1	4.0	.0	.0	3.2	.0	.0	1.1	4.0	1.1	.4	.0
SE	3.9	4.0	.0	.0	2.1	.0	.0	1.1	4.0	1.1	.4	.0
CV %	171.2	223.6	.0	.0	149.1	.0	.0	223.6	223.6	223.6	223.6	.0

Figure 4—Dwarf mistletoe table for one CVS plot.

DISTRIBUTION OF STANDING DEAD
BY DIAMETER CLASS

SAMPLE No.   1032148

	- - - - - - - - C O N D I T I O N - - - - - - -					
DIAMETER CLASS	HARD RECENT DEAD	HARD LOOSE BARK	HARD NO BARK	SOFT DECAYED SNAG	SOFT DECOMPS SNAG	TOTAL ALL SNAGS
2	99.6	.0	.0	.0	.0	99.6
4	20.0	4.0	4.0	.0	.0	28.1
6	4.0	4.0	8.0	.0	.0	16.0
8	20.0	4.0	12.0	.0	.0	36.1
10	8.0	8.0	.0	.0	.0	16.0
12	4.0	.0	12.0	.0	.0	16.0
14	3.2	2.1	2.1	.0	.0	7.4
16	.0	.0	2.1	.0	.0	2.1
18	.0	.0	.0	1.1	.0	1.1
20	.0	.0	.0	.0	.0	.0
22	.0	.0	.0	.0	.0	.0
24	.0	.0	.0	.0	.0	.0
26	.0	.0	.0	.0	.0	.0
28	.0	.0	.0	.0	.0	.0
30	.0	.0	1.1	.0	.0	1.1
32	.0	.0	.0	.0	.0	.0
STEMS/AC	158.9	22.2	41.4	1.1	.0	223.5
SD	200.1	32.2	43.6	2.4	.0	241.9
SE	89.5	14.4	19.5	1.1	.0	108.2
CV%	125.9	145.4	105.4	223.6	.0	108.2
SAMPLES	5	5	5	5	5	5
P(HAT)	1.00	.40	.60	.20	.00	1.00

WILDLIFE EXCAVATIONS BY STANDING DEAD CONDITION
(stems per acre 3.0" dbh and larger)

EXCAVATIONS	HARD RECENT DEAD	HARD LOOSE BARK	HARD NO BARK	SOFT DECAYED SNAG	SOFT DECOMPS SNAG
No Excavations larger than 1 inch.	59.3	22.2	41.4	.0	.0
One or more Excavations larger than 1 inch.	.0	.0	.0	1.1	.0

Figure 5—Table describing standing dead trees by 2 inch size class and decay class for one CVS plot.

```
WINEMA N.F.
KLAMATH R.D.          DISTRIBUTION OF DOWN WOODY MATERIAL      R6/NR-FID
SAMPLE No. 1032148                                           DATE:04/14/97
SAMPLE DATE:09/10/93
==============================================================================
              PIECE      TRANSECT   NUMBER OF
CATEGORY      DIAMETER   LENGTH     SAMPLES     MEAN      SE       CV%
------------------------------------------------------------------------------

AVERAGE PIECE COUNT PER SAMPLE:

             .2 -  .9 in.  10.0 ft.      5       16.6     7.8      104.7
            1.0 - 2.9 in.  10.0 ft.      5        2.6     1.2      103.9
            Over 3.0 in.   51.1 ft.      5        2.8      .5       39.1

AVERAGE WEIGHT IN TONS PER ACRE:

             .2 -  .9 in.  10.0 ft.      5        4.4     2.8      140.5
            1.0 - 2.9 in.  10.0 ft.      5        5.2     3.5      147.8
            Over 3.0 in.   51.1 ft.      5        6.9     1.4       44.5

AVERAGE PIECE COUNT PER ACRE:

            3 - 11.9 in.   51.1 ft.      5      254.3    87.7       77.1
           12 - 19.9 in.   51.1 ft.      5       20.8     8.8       94.5
           20 & Over in.   51.1 ft.      5        .0      .0        .0

            Over 3.0 in.   51.1 ft.      5      275.1    89.6       72.8

AVERAGE PIECE LENGTH :

            3 - 11.9 in.   51.1 ft.     10       22.0
           12 - 19.9 in.   51.1 ft.      4       53.5
           20 & Over in.   51.1 ft.      0        .0

            Over 3.0 in.   51.1 ft.     14       31.0

AVERAGE CU. FT. VOLUME PER ACRE:

            Over 3.0 in.   51.1 ft.      5      549.9   109.4       44.5

==============================================================================


CONDITION AND CAVITY/FORAGE USE OF LARGE PIECES:

                                      Sapwood    Interior
                             Mostly    Decay      Decay
   USE CATEGORY              Sound    Present    Present
------------------------------------------------------------------

No Excavations                 .0       81.0      177.8
larger than 1 inch.

One or more Excavation         .0        6.5        9.8
larger than 1 inch.

------------------------------------------------------------------
```

Figure 6—Table describing pieces per acre and tons per acre down
wood by category for one CVS plot.

1032148.KEY

```
STDIDENT
1032148     WINEMA N.F.    KLAMATH R.D.    CVS Sample Grid = 3.4 mile.
INVYEAR         1993
STDINFO         620     CRS112      143          0           19          61          46
DESIGN          0           1       999          5
ECHOSUM
DELOTAB         1
DELOTAB         2
SCREEN
MGMTID
WRD1

RRIN
SAREA           2.5
RRTYPE          1
RRINIT          0           2                                .4          1.0
RRTREIN
RRDOUT
PLREAD
    2
    4
-999
STREAD          RF          2           3.
END
```

1032148.FVS

```
000113320.0461MH  100  0  0   0   0698 0   0 0 0 02019200   050         1032148 1
0001102 5.3101LP  130  0  0   0   0398 0   0 0 0 02019200   050         1032148 1
000111920.0461MH   32  0  0   0   0530 198 0 0 0 02019200   050         1032148 1
0001104 5.3101LP  144  0  0   0   0430 298 0 0 0 02019200   050         1032148 1
000112120.0461RF   31  0  0   0   0350 198 0 0 0 02019200   050         1032148 1
000112220.0461MH   30  0  0   0   0698 0   0 0 0 02019200   050         1032148 1
0001107 5.3101LP  153  0  0   0   0398 0   0 0 0 02019200   050         1032148 1
0001108 5.3101LP  133  0  0   0   03 0 0   0 0 0 01019200   050         1032148 1
0001109 5.3101LP  147  0  0   0   0398 0   0 0 0 02019200   050         1032148 1
   :
   :
0005000     3981MH    1  0  0   0   00 0 0   0 0 0 01019200   050         1032148 5
0005000     2981RF    1  0  0   0   00 0 0   0 0 0 01019200   050         1032148 5
0005181 5.3106RF  143  0  0   0   00 7 340 2 0 02019200   050         1032148 5
000518520.0466RF   80  0  0   0   00 7 446 4 0 02019200   050         1032148 5
0005494 5.3109RF  178  0  0  23   0096 646 4 0 02019200   050         1032148 5
000519320.0466RF  101  0  0   0   00 7 498 0 0 02019200   050         1032148 5
-999
```

Figure 7—FVS keyword set describing one CVS plot. Set includes Western Root Disease model-ready keywords depicting current plot-level root disease impacts (lines 12 to 23) and FVS ready tree list.
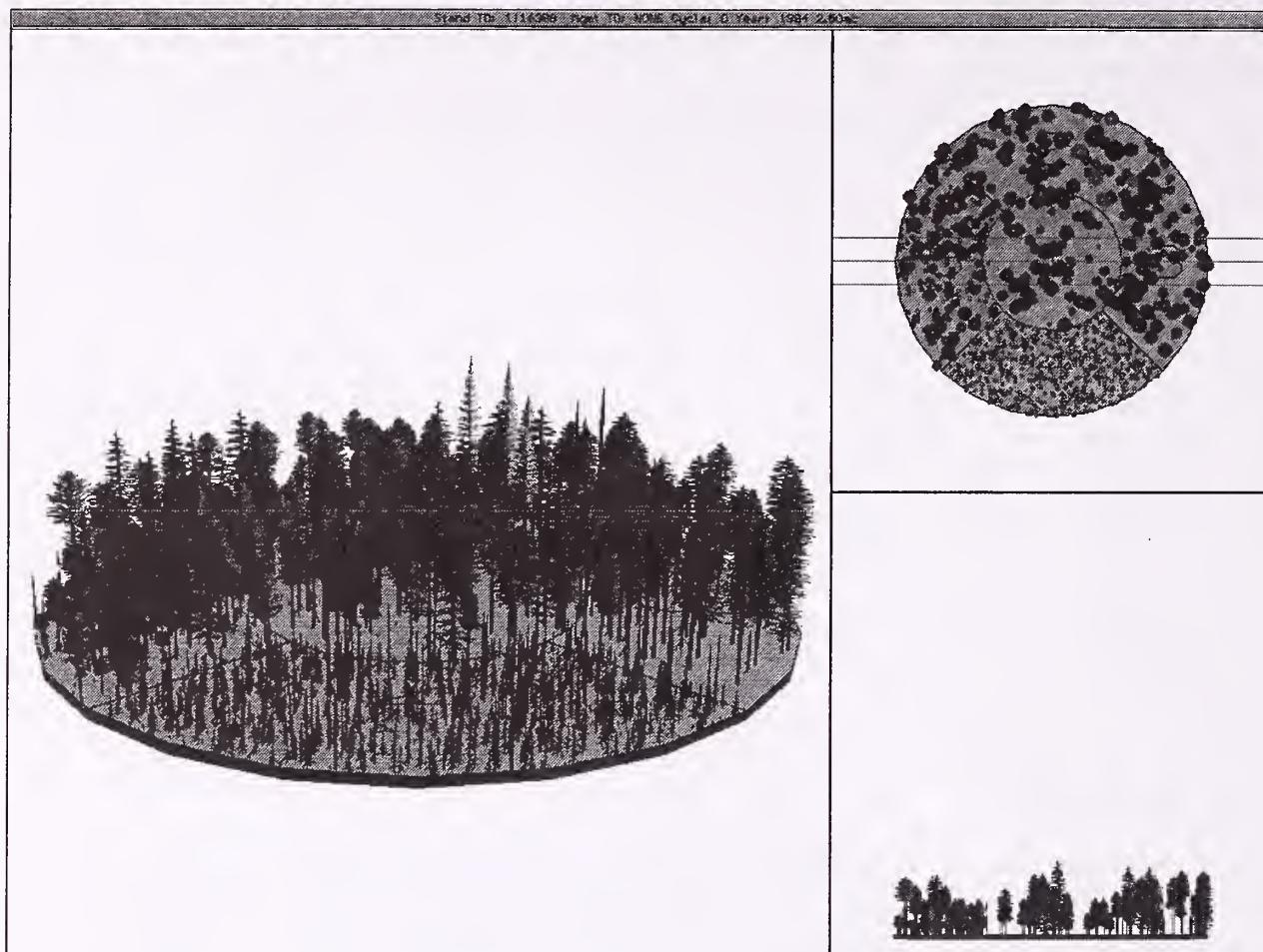
Figure 8—SVS image of the circular plot with trees distributed according to their subplot.

Conclusions

In general, the information that is coming from the inventory at the group code level of resolution seems reliable, particularly related to incidence. Pathologists and entomologists working with the data will undoubtedly have some adjusting to do, particularly related to root disease, when they attempt large scale analyses; however, that was assumed to be likely when the inventory was designed. In some respects, that close scrutiny will be valuable because it will involve the pathologists and entomologists more closely in the National Forest planning process.

These data also afford a great opportunity to analyze for insect and disease hazard related to site characteristics. The information will also allow us to look at thousands of individual trees for wildlife habitat characteristics, use, and damage and severity codes. The plot system supplies us with another set of permanent plots to include in our own model validation and calibration efforts. It also provides us with additional information to include in Forest Health Monitoring efforts.

Most important is the direct availability of insect and disease information at the plot level for those involved in

Forest or landscape-level planning and analysis. The impacts of our most important insects and diseases are described in such a way that they can be modeled with the vegetation, rather than considered as an "across the board" falldown in volume after the yield tables are built. Any pooling of plots for analysis can also take into account insect and disease impacts on vegetation.

Our involvement in the CVS process has been rewarding. We continue to provide training and consultation, participate in discussions regarding procedural revisions, and have recently begun to analyze these data for large scale impact assessment. Our participation in Forest and landscape-level analyses will be more valuable as a result of this data source.

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An Introduction to the Fire and Fuels Extension to FVS

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Albert R. Stage

Abstract—The Fire Effects Model Extension is a new extension to FVS and the PPE that allows users to simulate the effects of fire on a number of indicators, including stand structure and composition, fuel loading, and size and density of snags. In the absence of fire, the model can be used to simulate snag and fuel dynamics resulting from tree growth and mortality and stand management. While the model produces indicators of stand risk to fire (in terms of potential flame length), the model cannot be used to simulate fire spread or the probability of a fire. A brief description of the model is given here, with some sample results showing some of the new indicators at the stand and landscape level.

Fire is an integral part of forest ecosystem dynamics and management. The Forest Vegetation Simulator (FVS) (Stage 1973; Wykoff and others 1982) is used widely by forest managers to predict future forest conditions as affected by various management actions. Up to now, fire as an ecosystem process has not been explicitly represented in FVS. Outside of FVS, several models have been developed to represent fuel dynamics (with and without fire) (Keane and others 1989), the fire itself (Albini 1976a; Rothermel 1972), and the effects of fire (Keane and others 1989; Reinhardt and others 1997). The Fire Effects Model Extension (FEME) (Beukema and others 1996) was created from a need to link FVS with these fuel and fire models. The two main objectives for the FEME were to simulate fire effects (but not fire

spread or the probability of fire), and, where possible, to use established algorithms and existing models. A joint model allows the fuel and fire model components to benefit from FVS by using FVS-generated predictions of tree growth, mortality, and regeneration as they are influenced by simulated management practices, and allows FVS components to benefit by being able to directly represent the effects of fire on species composition and stand structure. In the absence of fire, the snag model component of the FEME provides predictions on the dynamics of dead trees which are of interest to wildlife biologists and forest managers.

Brief Description of the Fire Effects Model Extension

Model Overview

The FEME includes several submodels that take information from other components, perform calculations, and pass other information to different components (fig. 1). The three main submodels are: a snag model, a fuel dynamics model (which includes a foliage or branch model), and a burn model (which includes a fire intensity model and a fire effects model). As with the insect and disease extensions to FVS, the FEME uses the tree data generated by FVS to perform various calculations. Each of the submodels, and the information they use and generate, will be described in more detail.

Currently, the FEME is linked to the Northern Idaho variant of FVS and of the Parallel Processing Extension (Crookston and Stage 1991). This allows users to simulate fire effects at the stand and landscape level, although fires at the landscape level will not spread between stands.

Snag Model

The snag model tracks the fate of the stem and crown (foliage and branches) of standing dead trees. In the model, snags are stored in groups of trees that died in the same year and are in the same species-, diameter-, and height-class. The snags in each record are described by seven characteristics:

Figure 1—Overview of the components of the model and their interaction. The boxes in this figure show the main submodels while the arrows indicate the flow of information between submodels.

1. Two-inch diameter class based on the diameter at the time of death
2. Species
3. Current height
4. Height at the time of death
5. Time since death
6. Decay status (hard or soft)
7. Snag density (trees per acre)

Only four of these characteristics change over time: density, height, decay status, and time since death. Trees can become snags through stand management, fires, or natural death. The number of snags per acre is reduced through fall down or management. The remaining snags will experience some breakage or height loss. The annual rate of this loss depends on species and will affect the calculated snag volume. The branch and stem material lost from the snags through fall down or height loss is transferred to the fuel pools. Finally, as the snags decay, hard snags will become

soft. The parameters driving each of these processes are under keyword control.

Keywords are available to allow users to remove snags of given ages and decay states (for example, do a salvage cut), and to create snags either as part of a regular harvest (for example, trees that are killed as a result of the harvest but are left standing) or as an entry that is designed to create "wildlife" trees. A keyword allows users to add snags to the stand inventory at the start of the simulation. These snags are considered to be in addition to the dead trees in the treelist.

Output is available that gives the density, height, volume, decay class, and time of death for all snags in the model. These values are grouped into one to six classes based on stem diameter at the time of death. Class boundaries and output frequency are under user control.

Fuel Dynamics Model

In the FEME, fuels are defined as organic material on the ground. This includes woody material of any size, litter, duff, and live herbs and shrubs. The woody fuels are stored in six different size classes, based on piece diameter: 0 to 0.25 inch, 0.25 to 1 inch, 1 to 3 inches, 3 to 6 inches, 6 to 12 inches, and greater than 12 inches. Input to the litter and woody fuel pools comes from snags (breakage and falling), litter fall, canopy breakage (from tree growth, scorching, or other causes), and residue from harvest. As the fuels in the fuel pools decay, the material either enters the duff pools, or is oxidized to the air. Decay rates are based on the size and type of fuel and are modeled using a simple exponential decay process. Fuels that have come from soft snags decay faster than those from hard snags, and litter and small fuels decay faster than larger fuels. Besides the transfer of material to the duff pool as part of the decay process, there is no transfer of material between size classes. Decay rates and the proportion of the decayed material that is transferred to the duff pools are all under user control.

The live herbs and shrubs are not modeled explicitly. The biomass in these classes depends on the dominant species in the stand. It is a constant, using the assumption that the herbs grow back within 1 year of fire and their volume will compensate for the slower regrowth of the shrubs. At this time, herbs and shrubs only affect the amount of smoke produced by the fire.

Because the fuel model receives input from the canopy of live trees, there is a separate submodel that uses tree information (species, diameter, relative position in the stand, and so forth) from FVS to determine the amount of foliage and branch material in the canopy of each tree. The amount of canopy breakage and litter fall entering the fuel pools can then be calculated for both live trees and snags.

Fuel levels in the model can be reduced using various fuel burning options such as, pile burns or jackpot burns, as well as prescribed burns. Additions to the fuel pool at the time of harvest are also under keyword control. The fuel model output reports the amount of fuel in litter, duff, small and large fuel classes, and includes summary information on small and large snags, and small and large live trees.

Burn Model

The burn submodel consists of two parts: calculations of fire intensity and calculation of fire effects. Fire intensity, using flame height, is directly based on a routine in the existing FIRESUM model (Keane and others 1989) that is based on the FIREMOD model (Albini 1976b). Inputs to the fire intensity calculations include moisture, windspeed and the characteristics of small fuels. The characteristics of small fuels are calculated from equations derived from the standard static fuel models (Albini 1976a) and use the small and large fuel loads from the fuel dynamics model.

The model calculates various fire effects, many of which are based on algorithms in FOFEM (Reinhardt and others 1997). The effects include: tree mortality, fuel consumption, smoke production, growth reduction of scorched trees, and fuel creation (from fire-killed canopies). Tree mortality in the model is primarily based on flame height and scorch height, and varies by species and diameter. Additional mortality can be caused by crown fires. Fuel consumption is based on moisture and fuel class and directly affects the amount of smoke produced.

Users must select the year and stand in which fires occur. A keyword controls the type of fire (for example, prescribed fire, wildfire, throttle back, or mass ignition). Each type determines the default windspeed or flame length that is used for the fire. Additional keywords allow users to change the conditions at the time of a burn: moisture levels, windspeed, temperature, flame length or flame length multiplier, and percent of stand experiencing crowning.

At the time of a fire the model reports, if requested, the burn conditions (moisture, windspeed, flame length, and so forth), tree mortality by species and size class, fuel consumption, smoke production and percent of the stand that experienced crowning. Users may also request output that gives an indication of the risk of stands to different types of fire. This table contains the potential flame length for prescribed burns and wildfire. Finally, if the fire model is run as part of the PPE, landscape-level reports can be produced that show the amount of the landscape in different fuel load classes, by fuel pool, and the percentage of the landscape that would experience flame lengths of different categories for prescribed burns and wildfire.

Results

Two scenarios were simulated using stand data from the Nez Perce National Forest. The scenarios demonstrate the model's ability to produce different effects from occasional stand-replacing fires and from frequent underburns. In the first scenario, 60 percent of the landscape experienced two severe wildfires, the first 50 years after the start of the simulation and the second 100 years later. In the second scenario, underburns occurred every 20 years in the entire landscape.

Results from one of the stands that experienced the fires in the first scenario are presented here as an example. While the numeric values of the results vary between stands, the general dynamics are similar, especially the effect of the fires. Differences between stands arise primarily due to
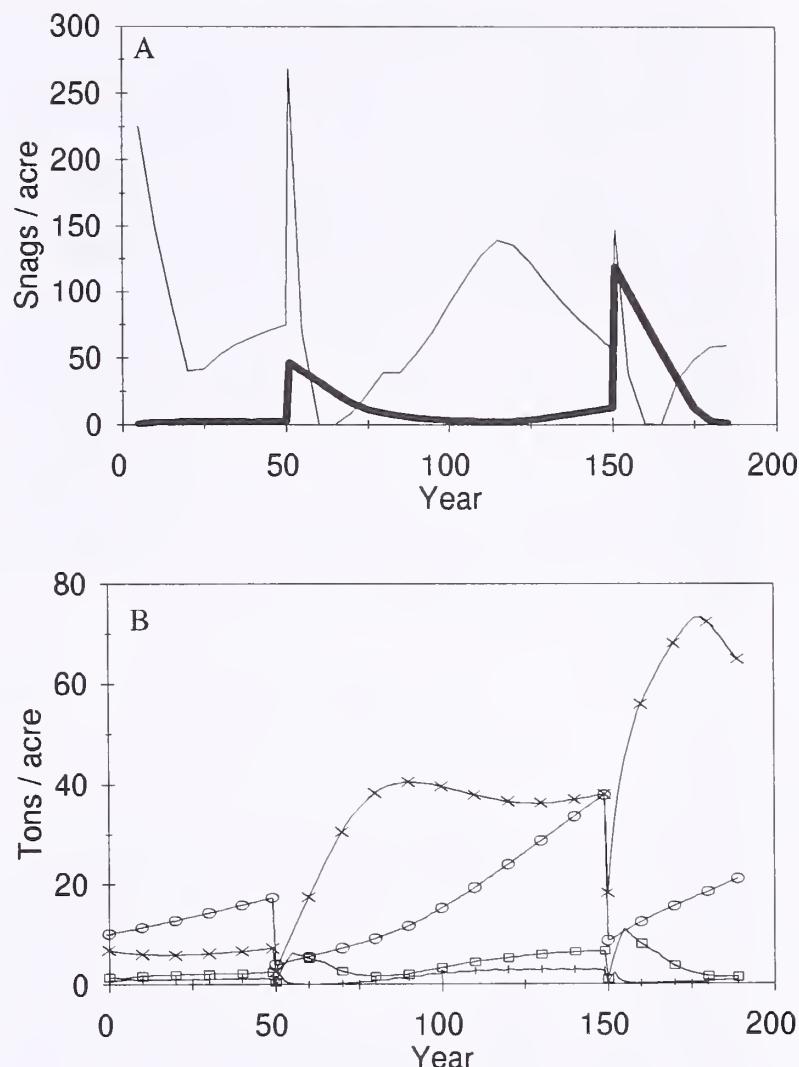
Figure 2—Example indicators from one simulation of the FEME. Severe wildfires occurred in year 50 and year 150. (A) Density of snags less than 12 inches diameter at the time of death (thin line) and greater than 12 inches diameter (thick line). (B) Fuel pools. Pools are: litter (∣), duff (○), fuels less than 3 inches diameter (□), and fuels greater than 3 inches diameter (✕).

different initial size and species compositions. The fires occurred under "very-dry" conditions with 90 °F temperatures and a midflame windspeed of 2 mph. Flame lengths ranged from 2.3 to 11.0 ft, and for the stand pictured here were 2.3 and 4.2 ft for the first and second fire, respectively.

Standard FVS stand dynamics have not been pictured here. The fire kills trees from all size classes and of all species, but mortality is higher on the smaller trees. The stands regenerate after the fires, and thus are about 100 years old at the time of the second fire.

In this scenario, the stand initially contains a large number of small dead trees (fig. 2a). These slowly fall and break apart. New snags are created through tree mortality. Immediately after the fire, the number of snags, both large and small, increases dramatically with the input of the fire-killed trees. The fall rate of small, fire-killed snags is higher than for trees killed by other causes, and thus the pool of

small snags decreases rapidly. The increase of small snags between fires is from natural mortality of the regenerating trees. At the time of the second fire, bigger trees are present, so the pool of large snags increases by a larger amount than after the first fire.

The debris pools show the opposite pattern. While all pools increase slightly in the first 50 years of the simulation, they all show a dramatic drop at each fire due to fuel consumption (fig. 2b). Seventy-seven percent of the duff pool was consumed in each fire and 64 percent (first fire) or 52 percent (second fire) of the large fuels was consumed. Fuel pools, especially the large downed woody debris, increase after the fire due to input from the falling and breaking snags. Duff pools show the most noticeable increase a number of years after the fire. As material decomposes in all other fuel pools, a portion enters the duff pool. Material enters at a faster rate than the rate of decay of the duff layer. Litter pools remain relatively constant throughout the simulation period with the exception of their consumption during a fire.

The simulations were done using the PPE version of the model. Thus, the model produced output that showed the percent of the landscape that was in different fuel loading classes, for certain fuel pools. Fuel loading classes are defined as 0 to 10 tons per acre, 10 to 20 tons per acre, 20 to 30 tons per acre, and greater than 30 tons per acre. Figure 3 shows the results of the landscape-level simulation on the small fuel loading (fuels less than 3 inches). Initially, the entire landscape contains less than 10 tons per acre of small fuels. As the landscape ages, the amount of small fuel increases. The first fire occurs in year 50 and its impacts are easily seen as the increase in the area containing small fuels. The second fire is also noticeable because in year 150, 60 percent of the landscape, the amount of area burned, contains less than 10 tons per acre of small fuels.

Figure 4—Landscape-level fuel loading of small fuels (0 to 3 inches diameter) in the scenario with frequent underburns. The y-axis shows the percentage of the landscape in each of four loading categories, measure in tons per acre.

This result contrasts with the same landscape-level indicator in the second scenario. In this scenario, repeated underburns prevent the small fuels from accumulating in the landscape (fig. 4).

Summary

The FEME is a flexible model that allows users to simulate snag and fuel dynamics with or without fires; predict changes in fuel levels due to management, fire, or natural aging; calculate a fire severity indicator for the stand or landscape; and predict the effects of fire on various indicators, including stand structure and composition. The fire model cannot, however: predict when a fire will occur, calculate the probability of a fire, or simulate the spread of fire between stands.

The model is still in a state of testing and calibration, especially the fuel dynamics components. Additional refinements to the model will allow users to use the Event Monitor (Crookston 1990) to schedule fires based on live tree, snag or fuel conditions. In addition, the snag submodel will be integrated as a component of the base model FVS that will be available to users outside of the fire model.

Acknowledgments

Figure 3—Landscape-level fuel loading of small fuels (0 to 3 inches diameter) in the scenario with two stand-replacing fires in 60 percent of the landscape. The y-axis shows the percentage of the landscape in each of four loading categories, measured in tons per acre.

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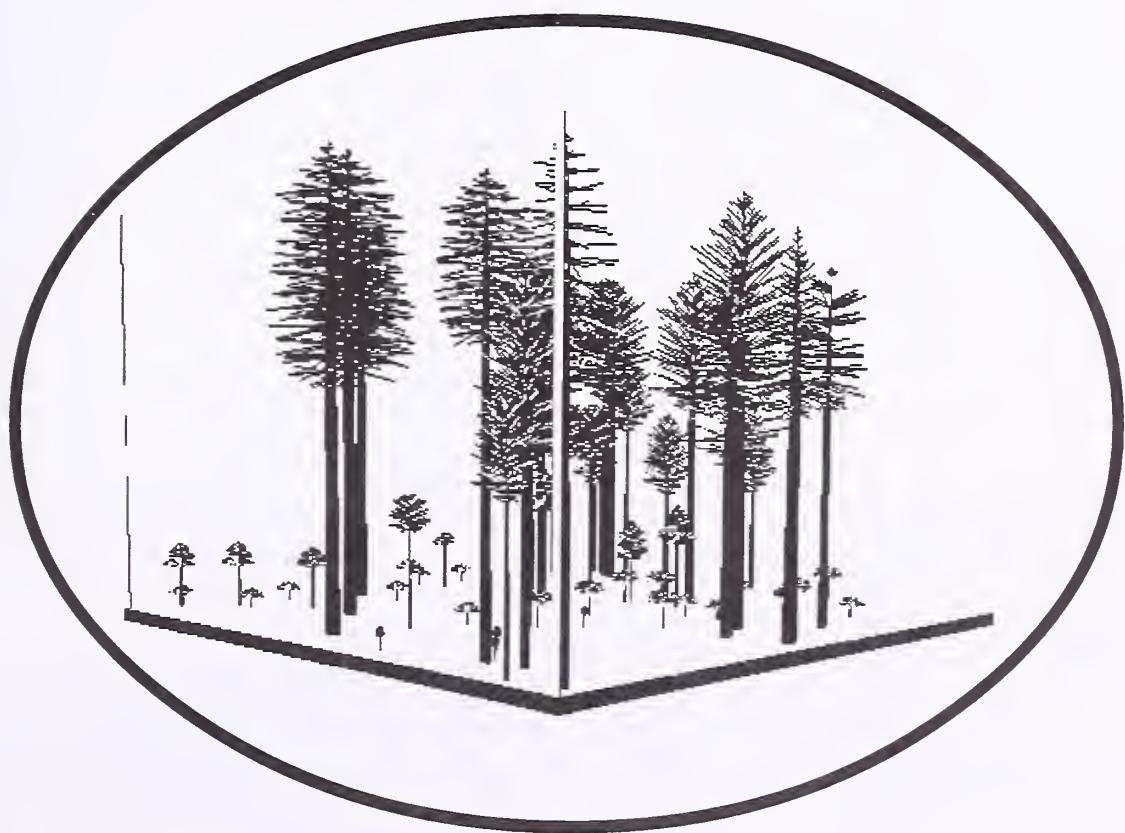
Predicting Basal Area Increment in Irregular Stands: a Progress Report

William R. Wykoff

Abstract—Point or sub-plot density provides some spatial context to basal area increment predictions in irregular stands. However, both point and stand density have measurement errors that are related to the size and number of sample plots. When independent variables are measured with error, ordinary least squares parameter estimates are biased toward zero. Error-based parameter estimates (structural model) were compared with ordinary least squares estimates (OLS model) for five northern Idaho tree species. In addition, alternatives to basal area percentile were evaluated as indices of relative size. Compared with OLS models, structural models were more sensitive to point and stand density effects and less sensitive to crown ratio. The best relative size variable assigned the same competition value to classes of trees such that all members of a class had diameters greater than 90 percent of the diameter of the largest tree in the class.

Current Federal forest management directions emphasize irregular stand structures. However, the Prognosis Model (Stage 1973; Wykoff and others 1982), which is the tree growth engine in the Forest Vegetation Simulator (FVS), assumes that stands are relatively uniform in spatial variation of stocking. For example, the basal area increment model developed for eastern Washington, northern Idaho, and western Montana (Wykoff 1990) uses competition variables that are based on stand crown competition factor (*CCF*) (Krajicek and others 1961), basal area (*BA*), and the size-rank of individual trees as represented by percentile in the stand basal area distribution (*PCT*). None of these variables account for spatial variation in competition.

Many forest inventories are based on multiple sampling locations systematically located within stands. Sampling locations are represented by random sample points and trees are sampled on fixed and/or variable radius plots centered on the sample points. By calculating density and size distributions for individual points, it is possible to account for some variation in the spatial pattern of stocking within a stand (Johnson and Dixon 1990). However, depending on the sizes of trees and associated plots, point-based competition estimates can have large measurement errors. When model parameters are estimated with ordinary least squares (OLS), estimates for variables with large measurement errors will be biased toward zero. Thus, although point density may serve to localize competition effects, competition may be confounded with a correlated variable. For example, crown ratio and basal area are highly correlated in natural stands and, given a large basal area measurement error, much of the associated competition effect could be carried by crown ratio.

Stage and Wykoff (1996) used measurement error methods (Fuller 1987) to develop a basal area increment model for Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) on the Nez Perce National Forest, Idaho. The model was based on the Wykoff (1990) model but included point estimates of competition variables. This report describes the extension of the 1996 model to include a wider geographic base and four additional species: grand fir (*Abies grandis* [Dougl.] Lindl.); western hemlock (*Tsuga heterophylla* [Raf.] Sarg.); western larch (*Larix occidentalis* Nutt.); and lodgepole pine (*Pinus contorta* Dougl. ex.Loud.). In addition, new transformations of crown ratio and relative size were evaluated.

The objectives of both the Nez Perce study and this extension were to improve the model representation of stands with irregular structure and to demonstrate procedures for estimating parameters and applying models when measurement error is a significant component of independent variables. Application of these procedures should also increase model reliability when the sampling design for data used to drive the model differs from the design used to collect calibration data. In particular, treatment of simulated regeneration should be less dependent on plot size.

Methods

The data for this analysis were extracted from the 1971 through 1974 forest management planning inventories for the six National Forests in northern Idaho and eastern Washington (Clearwater, Colville, Coeur d'Alene, Kaniksu, Nez Perce, and St. Joe). The first step was to fit the Wykoff (1990) model (eq. 1) to the data. The resulting model (1990 model) was used as the standard for evaluating subsequent model changes and fitting procedures.

$$\ln(dds) = \beta \; \{HAB, \; LOC, \; \ln(dbh), \; CR, \; CR^2, \; (1-PCT)*BA/\ln(dbh+1),$$
$$CCF_{hab}, \; dbh^2_{loc}, \; EL, \; EL^2, \; \cos(ASP)*SL, \; \sin(ASP)*SL, \; SL, \; SL^2\} \quad (1)$$

where:

dds	= 10 year change in squared diameter
HAB	= vector of habitat class dummy variables
LOC	= vector of location class dummy variables
CR	= crown ratio
dbh	= tree diameter at breast height
PCT	= percentile in the stand distribution of tree basal area
BA	= stand basal area
CCF	= crown competition factor
EL	= stand elevation

ASP = average stand aspect
SL = average stand slope ratio
β = a vector of associated regression coefficients.

Then, additional crown ratio, stand and point density, and relative size variables were evaluated for inclusion in the model. The "best" model form was fit with OLS and with measurement error techniques. All three models were evaluated by comparing behavior relative to predictor variables and by examining residual patterns for the calibration data and for an independent data set from young managed stands.

The Data

The management planning inventories were designed to obtain a representative sample of stands from all of the lands within the forest boundaries. The data extracted from these inventories sample a fairly broad geographic base with a wide range of diameters, point and stand densities, and sites (table 1). Initial dbh ranges from 3 to 65 inches, stand basal area from 1 to 320 sq ft, and point basal area from 6 to 600 sq ft. All size and competition data were backdated to the start of the 10 year growth period.

Alternative Variable Transformations

This analysis afforded an opportunity to examine the competition effects that are represented by transformations of density variables. Basal area in larger trees, derived from stand basal area and the percentile in the stand distribution of tree basal area, has proven to be an effective competition variable that responds appropriately when the stand is thinned (Wykoff 1990). However, the manner in which PCT is calculated can arbitrarily create differing competition effects for trees that are essentially the same size. In the extreme, if all trees are identical in diameter, one tree will have no competition, another one will have competition equal to stand basal area, and the remainder will have competition values evenly spaced between these extremes. Because predicted growth is strongly influenced by relative size, particularly as overall density increases, the predicted diameter distribution may have greater spread than expected. The performance of PCT was compared to two alternative variables that attempt to minimize artificial spread in the diameter distribution while retaining a meaningful relative size ranking. The fit of the three relative size measures was tested in combination with both point and stand basal area.

The first variable, dbh/D_{max}, is the ratio of tree diameter to the average diameter of the 40 largest trees per acre within the stand. Thus, trees that are the same size will experience exactly the same competition, and change in the competition effect will be continuous relative to diameter.

The second variable is an analog of PCT where trees of similar diameter are grouped, and all trees in a group are assigned the same competition level. The classification that performed best defined groups to include all trees with dbh within 90 percent of the dbh of the largest tree in the group. The competition level assigned to the group ($P90$) is the PCT of the largest tree in the next smallest group. While $P90$ treats similar sized trees the same, similarity is arbitrarily defined, and the change in competition effect relative to diameter is discontinuous.

In addition to relative size effects, three other model changes were examined. First, an alternative transformation of crown ratio was evaluated. This transformation included an interaction linking crown ratio effect to tree size (dbh). Next, alternative exponents for the location dependent dbh term were evaluated. In combination with the interaction between dbh and crown ratio, the best performance was obtained by replacing dbh^2 with dbh. The final change was the addition of a relative density term based on Curtis' (1982) index ($BA*d_q^{-1/2}$) where quadratic mean diameter (d_q) is replaced by the dbh of the subject tree.
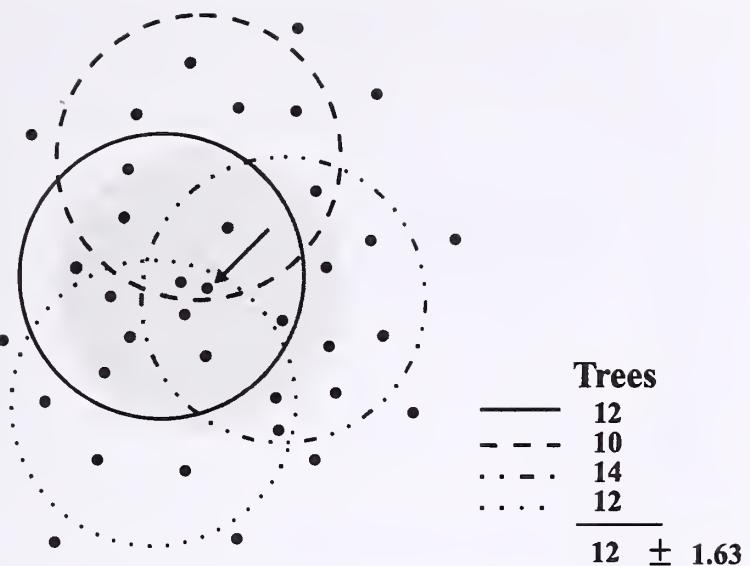
Measurement Error Calculations

The measurement error for stand basal was assumed to be the standard error of the mean point basal area (PBA). The measurement error for PBA was derived by assuming a Poisson model for the spatial variation in stocking.

The source of point basal area measurement error is illustrated in figure 1. In this example, a sample is obtained with a fixed-area plot. The subject tree, as indicated by the arrow, is included in the sample. The actual location of plot center is random relative to the location of the tree. Thus, a plot that is centered anywhere within the shaded circle will

Table 1—Stand and tree attributes for data used in diameter increment analysis for northern Idaho data.

| Attribute | Species | | | | |
	Douglas-fir	Grand fir	Western hermlock	Western larch	Lodgepole pine
Number of records	5307	3617	1372	2285	2492
Mean dbh increment (inch)	1.05	1.43	1.27	0.83	1.00
Minimum dbh (inch)	3.0	3.0	3.0	3.0	3.0
Mean dbh (inch)	14.4	15.2	16.3	14.7	8.8
Maximum dbh (inch)	55.1	64.9	60.0	49.4	26.1
Minimum stand BA(ft²/acre)	1.0	2.0	2.0	7.0	1.0
Mean stand BA (ft²/acre)	107.0	125.1	127.3	112.9	97.4
Maximum stand BA (ft²/acre)	319.0	319.0	259.0	295.0	295.0
Minimum point BA (ft²/acre)	6.0	7.0	16.0	10.0	10.0
Mean point BA (ft²/acre)	137.4	155.3	165.2	143.7	118.7
Maximum point BA (ft²/acre)	533.0	539.0	609.0	583.0	524.0

Trees
——— 12
– – – 10
· – · – · 14
· · · · 12
———
12 ± 1.63

Figure 1—The measurement error associated with point basal area. The circular shaded area around the subject tree (arrow) highlights possible random plot center locations that would include the tree. The circles represent four of the infinite possibilities. Variation in tree count between these samples (std. dev. = 1.63) reflects the magnitude of measurement error for competition.

include the subject tree. The various unshaded circles represent four such sampling realizations out of the infinite number of possibilities. In this case, the standard deviation of the mean number of trees is 1.63. Under the Poisson assumption, the variance would be equal to the number of trees obtained in the sample, resulting in a standard deviation ranging from 3.16 to 3.74, depending on which of the four samples was obtained. In this example, the trees are distributed more uniformly than would be predicted by the Poisson model. If the spatial pattern were perfectly uniform, there would be little variation of competition in space.

The Poisson model is a good starting point for natural stands, but in practice, adjustment of the variance estimate may be required to represent conditions that are more or less uniform. Such adjustments could be based on analysis of stem maps combined with tests of model sensitivity to variance assumptions (Stage and Wykoff 1996).

Analyses

The OLS model parameters were estimated using REX (Grosenbaugh 1967), and the structural model parameters were estimated with EVCARP (Schnell and others 1988), which is an error-model estimation algorithm. The error-model approach (Fuller 1987) computes parameters using OLS matrix operations except that the matrix of measurement error variances and covariances is subtracted from the moment matrix prior to inversion (eq. 2).

$$\beta = (X'X - \Sigma'\Sigma)^{-1}X'Y \tag{2}$$

where

X = the observation matrix of independent variables
Y = the observation vector of dependent variables

Σ = the matrix of measurement errors for independent variables

In this analysis, all error variances except for those related to stand and point density variables, and all covariances between measurement errors for the independent and dependent variables, are assumed to be zero.

Using the Structural Model for Prediction

The structural model parameters assume that variables have been corrected for measurement error. Therefore, for simulations based on the structural model (SBP), the structural coefficients must be dynamically adjusted to reflect current estimates of measurement errors as conditioned by tree diameter and plot size (Stage and Wykoff 1996). Thus, there are two keys to using the structural model for simulating stand development: measurement error variances must be estimable, and changes in the measurement error variances over simulated time must be predictable. The measurement error variance reflects the uncertainty of the sample as an estimate of the competition experienced by a subject tree.

Figure 2 illustrates the combined effect of basal area and basal area in larger trees on the predicted increment for a Douglas-fir with *dbh* of 5 inches. These prediction surfaces are based on the OLS and structural models (SM) developed for the Nez Perce National Forest (Stage and Wykoff 1996). The surface for the structural model is much more responsive to density, reflecting the fact that the competition variables used in the structural estimates for the associated parameters are free of measurement error. SBP predictions will vary between the OLS and SM surfaces depending on the magnitude of estimated measurement errors.

Results

The fit of the northern Idaho data to the 1990 model is summarized in table 2 along with sequential modifications. Mean square error (MSE) estimates for the 1990 model ranged from 0.23 for lodgepole to 0.32 for Douglas-fir. These values were consistent with estimates obtained in 1990 using data that included western Montana forests, were not censored for stand size, and had approximately twice as many total observations for each species. Replacement of *CCF* with *BA* resulted in little change in overall model fit. Whereas there was a slight improvement for Douglas-fir and lodgepole pine, fits for other species were slightly degraded. On balance, the simplification of measurement error variance calculations gained by substituting *BA* for *CCF* probably outweighs any loss in model resolution. Substitution of $CR/\ln(dbh+1)$ for CR^2 resulted in a slight reduction in MSE for all species except for lodgepole pine; changing D^2 to *dbh* had a similar result. These changes were not included in the final model for lodgepole but were retained for other species.

The relative size effect (basal area in larger trees) was modified by first replacing *BA* with *PBA* and then replacing *PCT* with the class-based *P90*. Again, slight reductions in MSE were obtained for all species. As an aside, the transformation dbh/D_{max}, which would have the advantage of eliminating arbitrary class boundaries, performed substantially
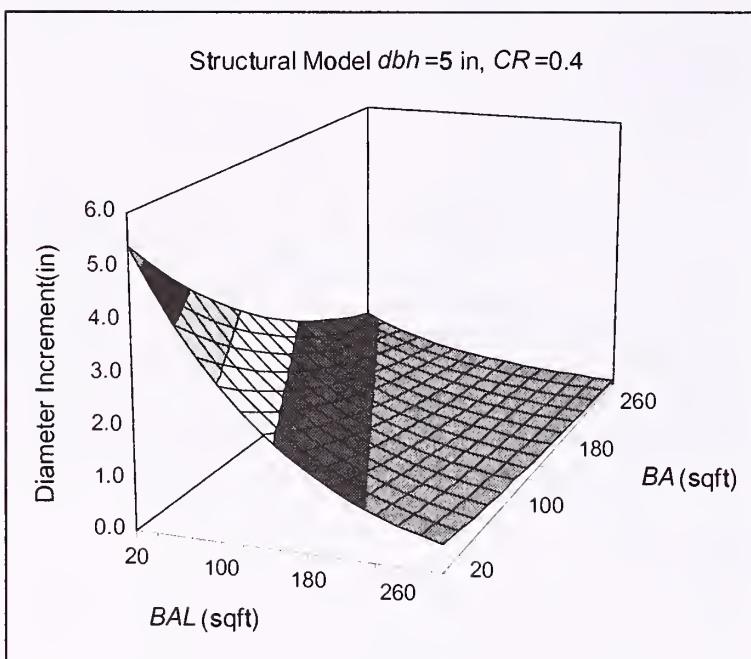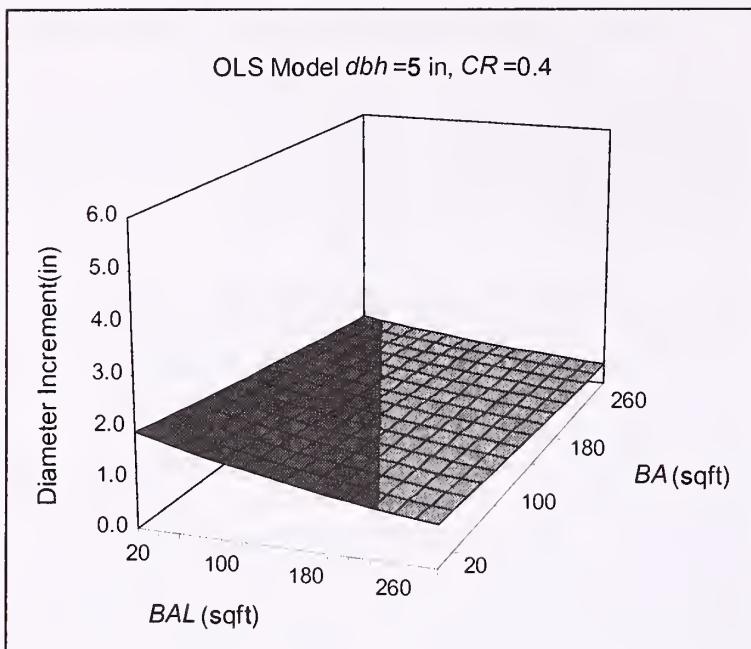
Figure 2—Predicted diameter increment as a function of *BA* and *BAL* for a Douglas-fir with 5 inch *dbh* on the Nez Perce National Forest; shading corresponds to graduations on the increment axis. The structural model surface assumes no basal area measurement errors and has much greater sensitivity to competition than does the OLS surface. In the SPB approach, measurement errors are included in the prediction, and the actual prediction will vary between the two surfaces depending on the magnitude of errors.

poorer for all species than did either of the percentile measures. Addition of $BA*dbh^{-1/2}$ resulted in a slight additional reduction in MSE for all species. In total, the changes reduced MSE by 1.7 to 5.4 percent relative to the fit for the 1990 model.

The final model (eq. 3) included a $CR/\ln(dbh)$ interaction, a relative size term based on *PBA* and *P90*, a habitat dependent *BA* term, a location dependent *dbh* term, and the $BA*dbh^{-1/2}$ interaction. Structural and OLS parameter estimates were obtained for this model.

$$\ln(dds) = \beta \{HAB, LOC, \ln(dbh), CR, CR/\ln(dbh+1),$$
$$(1\text{-}P90)*PBA/\ln(dbh+1), BA_{hab}, dbh_{loc}, BA*dbh^{-1/2},$$
$$EL, EL^2, \cos(ASP)*SL, \sin(ASP)*SL, SL, SL^2\} \tag{3}$$

Comparison of Model Residuals

Residuals were computed for the OLS and for SBP models using both the calibration data and a set of independent data. The independent data were derived from a 1974 through 1976 study of regeneration development (REGEN) that overlapped the period in which the management planning inventories were collected. For the calibration data, the patterns of residual $\ln(dds)$ for Douglas-fir (observed-predicted) show reasonable statistical properties for both OLS and SBP (fig. 3a,b). For the range of predicted values, the median residual is close to zero and the variance of the distribution of residuals is relatively homogeneous. The range of residuals for SBP is slightly larger than the range for OLS.

The lines in figure 3 are called midmean lines (Cleveland and Kleiner 1975) and connect the 25, 50, and 75 percentile points in the distribution of residuals within 10 percent classes of the ordinate variable. Figure 3c shows only the midmean lines for both models relative to *dbh* Again, no obvious trends emerge and differences in the patterns for the two models are minimal. Similar relationships were observed for all independent variables for all species.

Figure 4 illustrates the same relationships for the 770 Douglas-fir included in the REGEN data. On the average, both the OLS and SBP models overpredict increment for the REGEN data, with slightly larger average errors for the SBP model (fig. 4a,b). Note, however, that the data clouds evidenced here are wholly contained within the clouds shown for the calibration data (fig. 3a,b) and that the trend lines have little slope. Therefore, by adjusting the model intercept, most of the prediction bias could be removed. This is

Table 2—Changes in mean square error resulting from sequential changes in the model.

Change in model	Mean square error				
	Douglas-fir	Grand fir	Western hemlock	Western larch	Lodgepole pine
Wykoff (1990)	0.3198	0.3005	0.2794	0.2954	0.2318
CCF to *BA*	0.3188	0.3008	0.2795	0.2957	0.2311
CR^2 to $CR/\ln(dbh+1)$	0.3188	0.3007	0.2794	0.2955	0.2316
Dbh^2 to *dbh*	0.3157	0.2981	0.2770	0.2934	0.2314
BA to *PBA*	0.3150	0.2852	0.2686	0.2918	0.2237
PCT to *P90*	0.3084	0.2851	0.2684	0.2919	0.2232
Add $BA*dbh^{-1/2}$	0.3050	0.2843	0.2674	0.2904	0.2230
Total change (percent)	−4.6	−5.4	−4.3	−1.7	−3.8
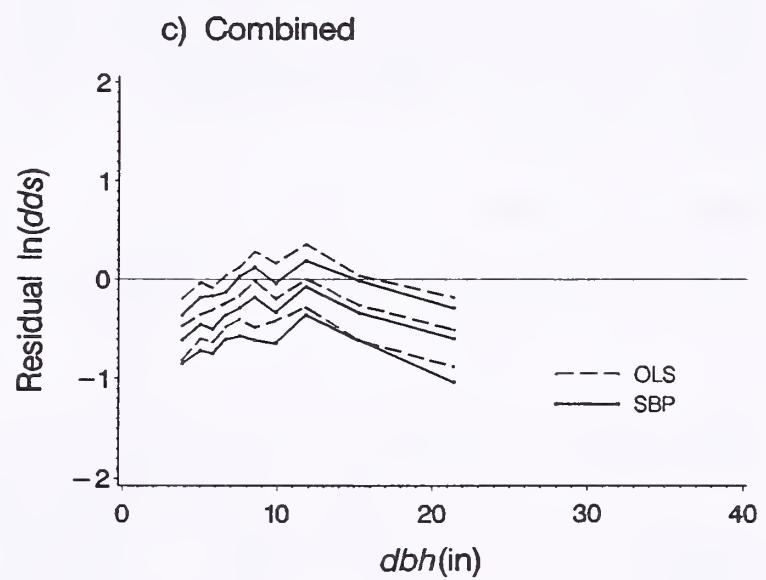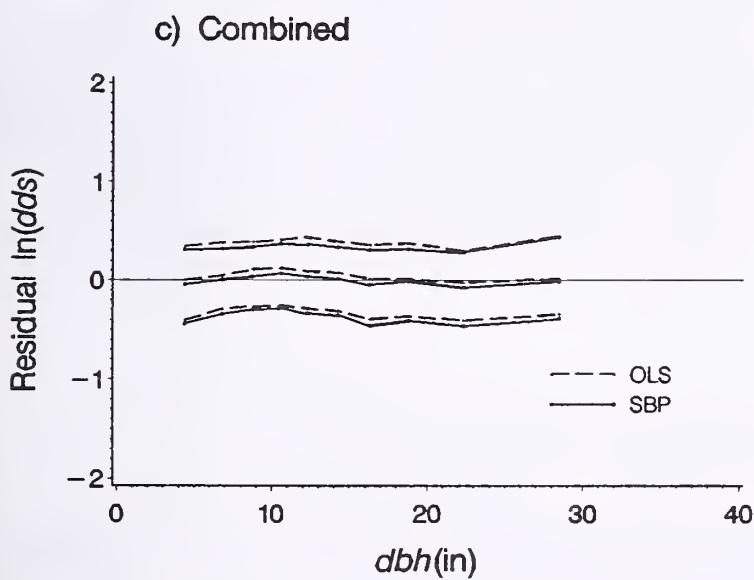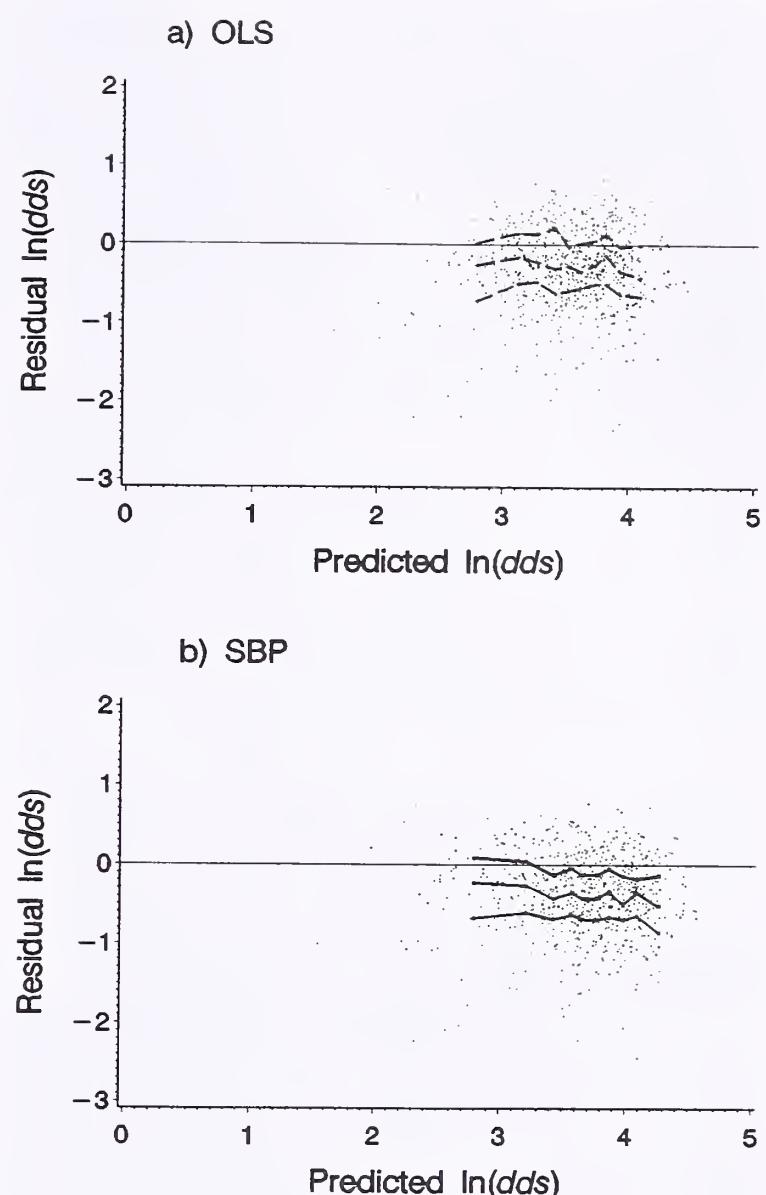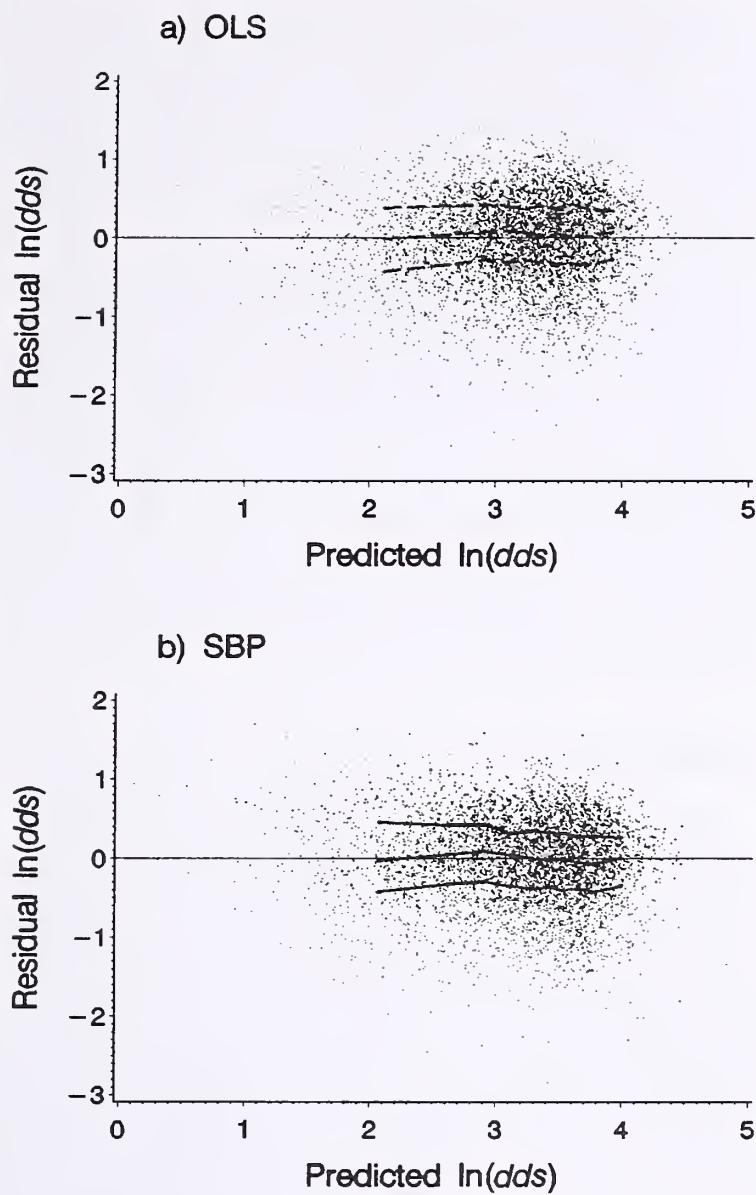
Figure 3—Residual patterns for the calibration data: (a) residual ln(*dds*) versus predicted ln(*dds*) for the OLS model; (b) residual ln(*dds*) versus predicted ln(*dds*) for the Prediction model; and (c) residual ln(*dds*) versus observed *dbh* for both models. The plotted lines connect the 25, 50, and 75 percentile points in the distribution of residuals for 10 percent classes of the independent variable (bottom to top, respectively).

Figure 4—Residual patterns for the REGEN data: (a) residual ln(*dds*) versus predicted ln(*dds*) for the OLS model; (b) residual ln(*dds*) versus predicted ln(*dds*) for the Prediction model; and (c) residual ln(*dds*) versus observed *dbh* for both models. The plotted lines connect the 25, 50, and 75 percentile points in the distribution of residuals for 10 percent classes of the independent variable (bottom to top, respectively).

analogous to the procedure used by FVS to calibrate the increment model when *dbh* increment is measured on a sample of input tree records. Thus, on an operational basis, overprediction is probably not a problem. The joint display of residuals relative to *dbh* (fig. 4c) shows considerable curvature, suggesting that overprediction is most pronounced for trees at the extremes of diameters represented in the REGEN data. Again, however, the predictions are within the range of predictions seen for similar sized trees in the calibration data, and patterns relative to other predictor variables showed little trend.

Table 3 summarizes bias and MSE for both models and both sets of data. In this table, mean square error has been corrected for bias as would occur with calibration in an FVS simulation. For the calibration data, the OLS predictions are unbiased while, on the average, the SBP predictions are slightly too large. Within species, the MSE is always lower for the OLS model, even when corrected for bias. This discrepancy ranges from 2.5 percent for western larch to 14.9 percent for lodgepole pine and probably reflects deficiencies in the measurement error variance models. If variances were known without error, the OLS and SBP predictions should match. The degree of the discrepancy, particularly for lodgepole pine, may reflect a tendency for spacing to be more uniform than would be predicted by the Poisson model. In this case, the Poisson model would overestimate measurement error in the model calibration data, resulting in structural coefficients that give more weight than appropriate to competition variables.

For the REGEN data, substantial overpredictions result for both models for all species. Again, the bias is always largest with the SBP model. On an encouraging note, for all species except for larch, MSE is less for the regeneration data than it is for the calibration data for both models. Furthermore, both OLS and SBP outperform the 1990 model (MSE = 0.2678 for Douglas-fir), and SBP outperforms OLS for Larch and Douglas-fir. Many anomalies remain and, based strictly on goodness of fit, it is arguable that a lot of effort was expended for little gain in performance. There are, however, behavioral properties of the models that deserve further consideration.

Model Behavior

Figure 5a contrasts the *CR* effects in the OLS and structural models (SM) relative to *dbh* Although behavior is not markedly different for larger trees, small trees are much less sensitive to *CR* in the OLS model. In natural stands, generally a high correlation exists between *CR* and stand density; therefore, in a statistical fit, *CR* can assume some of the competition effect, particularly if there are large measurement errors in the competition variables that are not accounted for in the fitting process.

The importance of stand basal area increases with *dbh*, and the effect is always stronger in the structural model (fig. 5b). The importance of relative size decreases with increasing diameter, but again the relative size effect is always stronger in the structural model (fig. 5c). Thus, there is a tradeoff between the relative importance of *CR*, which is affected indirectly by stand treatment and stand density, which is usually the target of treatment. This shift in emphasis to competition variables reflects the appropriate treatment of measurement errors. The SBP approach, in combination with the addition of point density effects, should improve model performance for both managed stands and stands with irregular structures.

Discussion

The SBP approach can be a valuable addition to FVS. Most important, the method gives statistical credence to the use of point density as a measure of within-stand variation in competition. For example, when beginning a simulation with inventories of regeneration stands or with tree lists created by a regeneration establishment model, the error in point density will become relatively large as trees become large. As the confidence in point density estimates decreases, it will receive less weight in the SBP approach. The combination of model revisions and the SBP approach appears to result in a desirable tradeoff between the correlated effects of crown ratio and competition. Thus, factors that are under direct control of cultural treatment are generally given greater weight in the prediction.

Assuming that guarded optimism is sustained by further experience with the model, the variance models should be further evaluated with stem maps and sensitivity analyses. Other models that include density effects should also be refit using error model techniques. In this regard, the crown ratio model should be given high priority. Finally, extension of the method to similarly constructed geographic variants will demonstrate whether the approach can be generalized across ecosystems.

Table 3—Bias and MSE for the OLS and SBP models shown for the calibration and REGEN data (MSE corrected for bias).

| Species | Calibration data | | | | REGEN data | | | |
| | Bias | | MSE | | Bias | | MSE | |
	OLS	SBP	OLS	SBP	OLS	SBP	OLS	SBP
Douglas-fir	0.0	−0.044	0.3050	0.3188	−0.271	−0.394	0.2564	0.2506
Grand fir	0.0	−0.025	0.2843	0.3007	−0.082	−0.158	0.2140	0.2176
Western hemlock	0.0	−0.008	0.2674	0.2840	−0.345	−0.356	0.2121	0.2788
Western larch	0.0	−0.042	0.2904	0.2976	−0.406	−0.432	0.3547	0.3381
Lodgepole pine	0.0	−0.072	0.2230	0.2562	−0.114	−0.189	0.1909	0.1928

a) *CR*
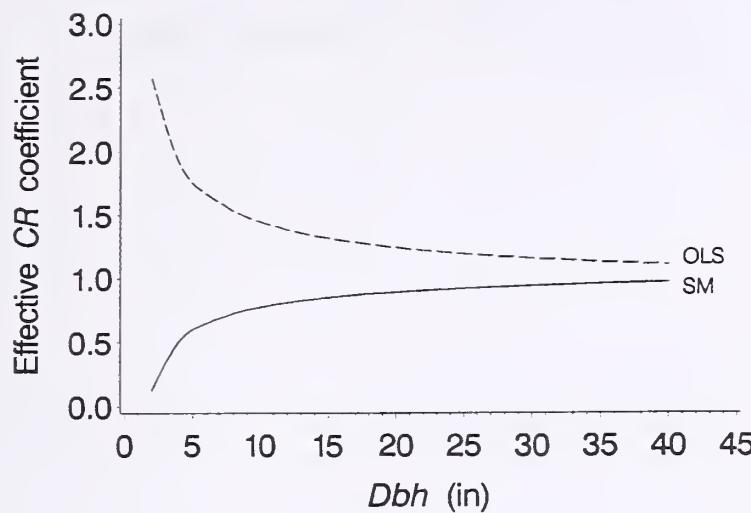
b) *BA*
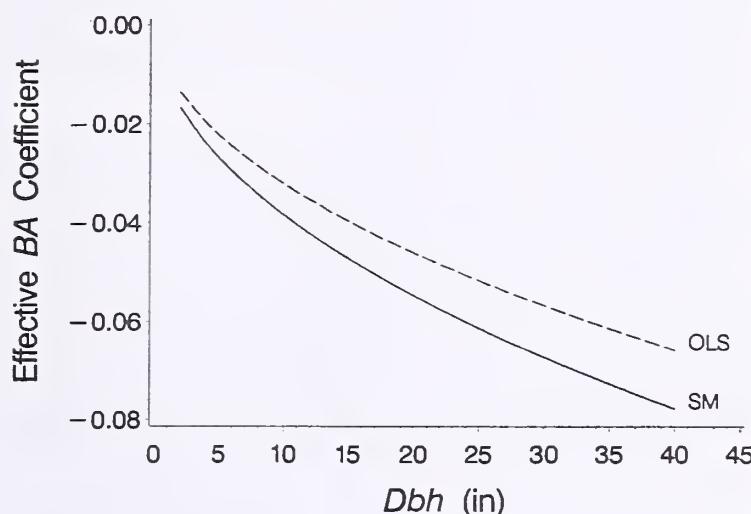
c) *BAL*
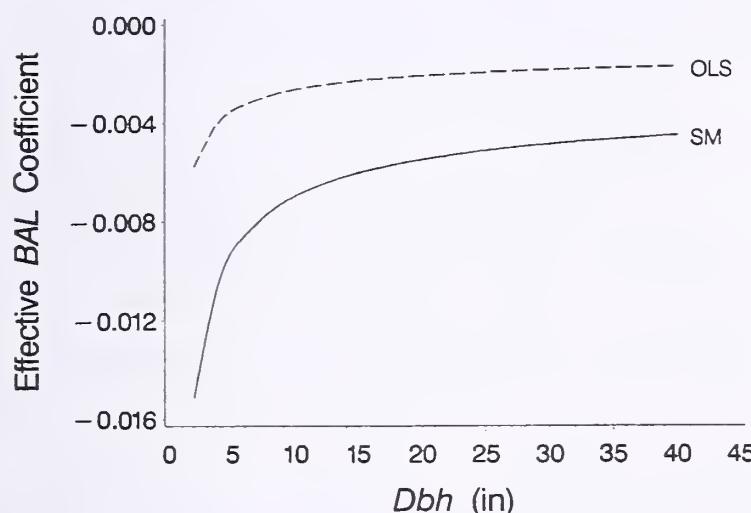
Figure 5—Comparison of effective coefficients for the OLS and structural model (SM) for varying *dbh*: (a) crown ratio (*CR*); (b) stand basal area (*BA*); and (c) basal area in larger trees (*BAL*).

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Exploring Partial Harvesting Options in the Nelson Forest Region, British Columbia

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Abstract—A metric variant of Prognosis (also known as the Forest Vegetation Simulator) has been linked to the Western Root Disease extension, and used to explore the interaction between partial harvesting, *Armillaria* root disease and productivity in 24 stratified combinations of ecosystem, stand composition and site productivity in the Nelson Forest Region, British Columbia. Besides a decline in productivity in the presence of root disease, the analyses show interactions among stand composition, timing of entries and level of removal, and that best-yield strategies change remarkably in the presence of root disease. Volume-age projections developed here have been further post-processed and linked to a landscape-level optimization model.

Projections of wood flow in the Nelson Forest Region in British Columbia indicate that there may be a near-term fall down in timber supply due, in part, to provincial cutting constraints and green-up requirements. To alleviate some of the impacts of this projected fall down, partial cutting has been proposed as one option that will provide timber in the short term, while not violating green-up constraints that limit clearcut logging. Root diseases (for example, *Armillaria ostoyae*, *Phellinus weirii*) are common in many ecosystem types in the Nelson Forest Region. Tree mortality due to root disease may increase following partial cutting (Morrison and others 1991). Reductions in standing volume after partial cutting due to root disease, windthrow, or other causes may also limit the utility of partial cutting as a tool to alleviate timber supply problems.

Because of the interaction between harvesting and subsequent root disease dynamics, planners need forest growth and yield models that will allow them to assess the possible outcome of partial harvesting on a stand and landscape basis. In British Columbia, the existing planning tools include the stand-based Variable Density Yield Projection System (VDYP, Version 6.3 b, Anonymous 1995a) and the Forest Service Simulator (FSSIM), a landscape-level forest estate optimization model. Neither of these tools were designed to include root disease dynamics or partial entries with subsequent ingrowth in the analysis options. As an alternative growth model, the Southern Interior (SI) variant of Prognosis (also known as Forest Vegetation Simulator) (version SI 1.0f, a metric version based on the Northern Idaho variant, version 6.1) (Stage 1973; Wykoff and others 1982) was designed to simulate uneven-aged, multi-species stands and partial harvests. With the Western Root Disease Model extension (WRDM3) (Beukema and Kurz 1996), Prognosis is able to incorporate the effects of root disease and its responses to stand entry.

The objective of the main study was to assess the utility of partial cutting as a tool to mitigate short-term timber supply shortfalls. The study contained three components: (1) developing response surfaces that describe changes in mean annual increment (MAI) over a range of management actions and root disease levels; (2) assessing the sensitivity of the results to changes in growth parameters; and (3) generating a series of volume-age curves for selected partial cutting scenarios for 24 combinations of biogeoclimatic ecosystem classification (BEC) subzone (Meidinger and Pojar 1991), timber type and site productivity class in the Cranbrook and Boundary Forest Districts of the Nelson Forest Region. These volume-age curves were then used in timber supply analyses using FSSIM. This paper summarizes results for the first component of the analysis. The complete study is described in Robinson and others (1996).

Methods

The 24 strata analyzed in this study included a low and a good/medium site productivity stand in each of six BEC subzone and timber type combinations in each of the Cranbrook and Boundary Forest Districts. The choice of BEC subzone and timber type combinations favored strata that are most likely to be scheduled for harvest within the next few decades, and reduced the emphasis on strata that are less prevalent or accessible across the landscape. Table 1 contains the tree species abbreviations used in BC, and table 2 provides ecological, species and site information for four of the strata discussed in detail here.

Initial efforts to find detailed stand information produced a number of Permanent Sample Plots (PSPs) with at least one remeasurement. Further examination showed that some of these plots had atypical species compositions when compared to area-weighted regional summaries, or that the site indices did not match those of the selected strata. Using alternative PSPs and Temporary Sample Plots (TSPs) we were able to replace some of these stands. Where gaps could not be filled, virtual stands were constructed from regional

Table 1—Conventional species abbreviations used in British Columbia.

Abbreviation	Common name
Cw	Western redcedar
Fd	Douglas-fir
Lw	Western larch
Pl	Lodgepole pine
Pw	Western white pine
Py	Ponderosa pine
Se	Engelmann spruce

Table 2—Stand composition and characteristics of four of the strata from good/medium sites in Cranbrook and Boundary Districts.

BEC subzone[a]	Timber type	Site index (M)	Stand ID	Species composition
				Percent
IDFdm2	FdLw	17.8	PSP 19-05-03	Fd 67, Lw 23, Pl 6, Py 4
MSdk	PlPure	17.9	PSP 20-02-01	Pl 100
ICHmw2	LwPure	23.7	*virtual*	Lw 63, Pl 20, Fd 14, Se 3
MSdm1	PlFd	19.0	*virtual*	Pl 70, Lw 16, Fd 14

[a]IDFdm2 = Dry mild interior Douglas-fir (variant 2)
MSdk = Dry cool montane spruce
ICHmw2 = Moist warm interior cedar hemlock (variant 1)
MSdm1 = Dry mild montane spruce.

compilations of the species composition, site index and site information.

Calibration and Validation

Prognosis simulates stand development, including the effects of ingrowth and thinning, by modelling individual tree growth. Its behavior is founded on regional habitat-type based parameter sets that can be calibrated further to accurately forecast growth for each tree species over a variety of site conditions. In the absence of a fully calibrated regional variant for British Columbia, we chose an alternative method for calibrating and validating the model's projections. We made use of the model's ability to self-calibrate when provided with periodic growth measurements from sample plots. We compared these self-calibrated volume-age curves with VDYP results for similar stand and site conditions. In cases where repeated diameter measurements were missing and self-calibration was not possible, we used VDYP to guide the growth parameter adjustments. In both instances, we used the BAIMULT keyword to maintain a fixed modifier for diameter growth.

All simulation runs were made using bare ground as the starting point. Even in cases where stand tree lists were available from TSP or PSP measurements, it was necessary to initiate Prognosis runs from bare ground because FSSIM requires volume-age curves for the complete rotation. In each stand, 2,000 stems/ha were planted, with the species mixture guided by the composition of the available PSP or TSP data, or in the case of virtual stands, by the regional average composition, as shown in table 2.

Stands with self-calibration information generally gave good fits to comparable VDYP runs. Those with no calibration were iteratively adjusted and in most cases gave a moderately good fit to VDYP runs. In some cases we were unable to obtain a good match between the volume-age curves of the two models. This lack of fit could arise from a number of causes attributable to either Prognosis or VDYP. Because VDYP is the current standard in BC, we chose to adjust Prognosis to give the best possible fit over the first century of growth, since this is the interval in which many of the harvesting options were exercised.

Analysis of Partial Harvesting Scenarios

Each stratum represents a unique combination of BEC subzone, timber type and site productivity class. Independent of BEC subzone or productivity, each timber type has unique characteristics that influence the choice of planting, thinning, and harvesting options. For example, in the FdLw (Douglas-fir dominant, western larch subdominant) timber type, partial cutting leaves Lw while Fd is left in the PlFd timber type.

One source of uncertainty in all the management scenarios is the quantification of ingrowth during natural stand establishment, either following disturbance or during periods of otherwise undisturbed growth. The species composition planted at the beginning of the first rotation does not include any ingrowth during periods of undisturbed growth. Ingrowth is simulated following partial harvest and following clearcut harvest between the first and second stand rotation.

For each of the 24 strata, we examined combinations of four factors: (1) stand age at first entry; (2) basal area removal level; (3) time between first entry and final harvest; and (4) amount of root disease in the stand. Because of the large number of possible scenarios, we divided the analysis into two levels of effort. For the stand-level MAI analysis, we operated over a fine scale for four stand types: first entry from 40 to 180 years in 10 year steps; residual basal area of 0 to 100 percent in 10 percent steps; time to final entry from 20 to 60 years after the first entry in 10 year steps; and root disease at none, light and moderate levels (see below). The detailed examination included a total of 2,475 simulations for each of the four BEC and timber type strata shown in table 2. At the landscape-level we used fewer levels of each factor, thus requiring 108 simulations for each of the 24 strata. These results were further post-processed to provide volume-age curves as input to the landscape-level FSSIM model.

Root Disease Scenarios

We defined three root disease levels for use in the simulations by varying the initial inoculum in each stand. During exploratory calibration, the initial inoculum levels were selected to yield impacts that were consistent with those observed by the regional pathologist. The initial inoculum consisted of five randomly located root disease centers covering 40 percent or 80 percent of the stand area for the "Light RD" and "Moderate RD" scenarios, respectively. Each patch contained recently dead infected stumps, with the species- and size-distribution of stumps derived from that observed at age 140 years in the corresponding bare ground calibration simulation. The third set of scenarios simulated stands free of root disease ("No RD").

Stand-Level MAI Response Functions _____

The detailed analyses of the stand-level response of MAI $(m^3\ ha^{-1}\ yr^{-1})$ to systematic changes in the four factors were conducted for four combinations of BEC subzone and timber type. All four strata showed broadly similar behavior. Examples of the response of MAI to variations in the four factors are summarized for the dry mild Interior Douglas-fir subzone (IDFdm2) with a Douglas-fir/ western larch timber type (fig. 1) and for the dry mild Montane Spruce subzone (MSdm1) with a lodgepole pine/Douglas-fir timber type (fig. 2). Viewing left-to-right, the columns show the MAI response surface for the No RD, Light RD and Moderate RD scenarios. Each of the rows shows a different delay to final harvest, with a 20 year delay on the top row, increasing to a 60 year delay on the bottom row. Each row and column object is a shaded contour plot with levels of residual basal area along the vertical axis and levels of age at first entry along the horizontal axis. Contour lines on these plots connect combinations of residual basal area and age at first entry having the same MAI.

The peak MAI in the "No RD" scenarios, shown in the figures as a set of concentric rings in the upper left panels, occurs in management systems based on early first entry, low levels of basal area removal followed by an early final entry. In the "No RD" scenario, the maximum yield is typically achieved with first entry at age 50 to 70 years, with about 80 percent residual basal area and final harvest 20 to 40 years later. Most of the changes in shape of the response surface are quite gradual, indicating that in the simplified world of the simulation there are no strong nonlinear responses which would produce surprising changes in behavior if the optimal condition could not be accurately known. A caveat to this general observation is the way the contour lines are more closely spaced on the left of the peak. Thus there is a more rapid change in productivity on the "young" side of the peak. This period of rapid change in MAI indicates that the stand's average productivity rises quickly prior to the optimum entry period, and argues for avoiding making entries on the young side of the optimum. This would be a poor strategy since any error in identifying the optimum could result in a very poor yield.

The two levels of root disease exert a number of similar effects across the four BEC subzone/timber type combinations. The first effect is a general reduction in MAI. The second effect depends somewhat on the level of root disease and the timber type, and is seen as a shift in the optimum (albeit lower) peak MAI toward large basal area removals with long delays between the partial entry and the final entry. This is seen as a shift in the peak MAI in the second and third column of figures 1 and 2. In effect, the optimum harvest strategy moves toward a clearcut management system with a rotation length of around 60 to 80 years. The third root disease effect is the small "hook" in the contour lines at the top of the panels in scenarios with root disease. This hook is caused by a nonlinear change that occurs between a partial entry with 90 percent residual basal area and no entry. It reflects the increased mortality and decreased productivity associated with the root disease response to partial cutting. This effect is small in the simulations and is consistent with the observations of pathologists.

Harvesting strategies usually involve trade-offs between volume yield and other considerations. Apart from the assessment of the impacts of *Armillaria*, harvest practices in the Nelson Forest Region must also comply with the B.C. Forest Practices Code (FPC). Based on the quantitative results of the fine scale simulations, we have derived stand productivity estimates that comply with different FPC requirements for good/medium sites under three harvest systems: best overall yield; partial harvest with 70 percent residual basal area (RBA), as per the Forest Practices Code Biodiversity Guidebook (Anonymous 1995b); and partial harvest with 40 percent RBA, as per the Forest Practices Code Green-up Guidebook (Anonymous 1995c). Table 3 shows one example of projected yield, based on root disease severity and harvest method.
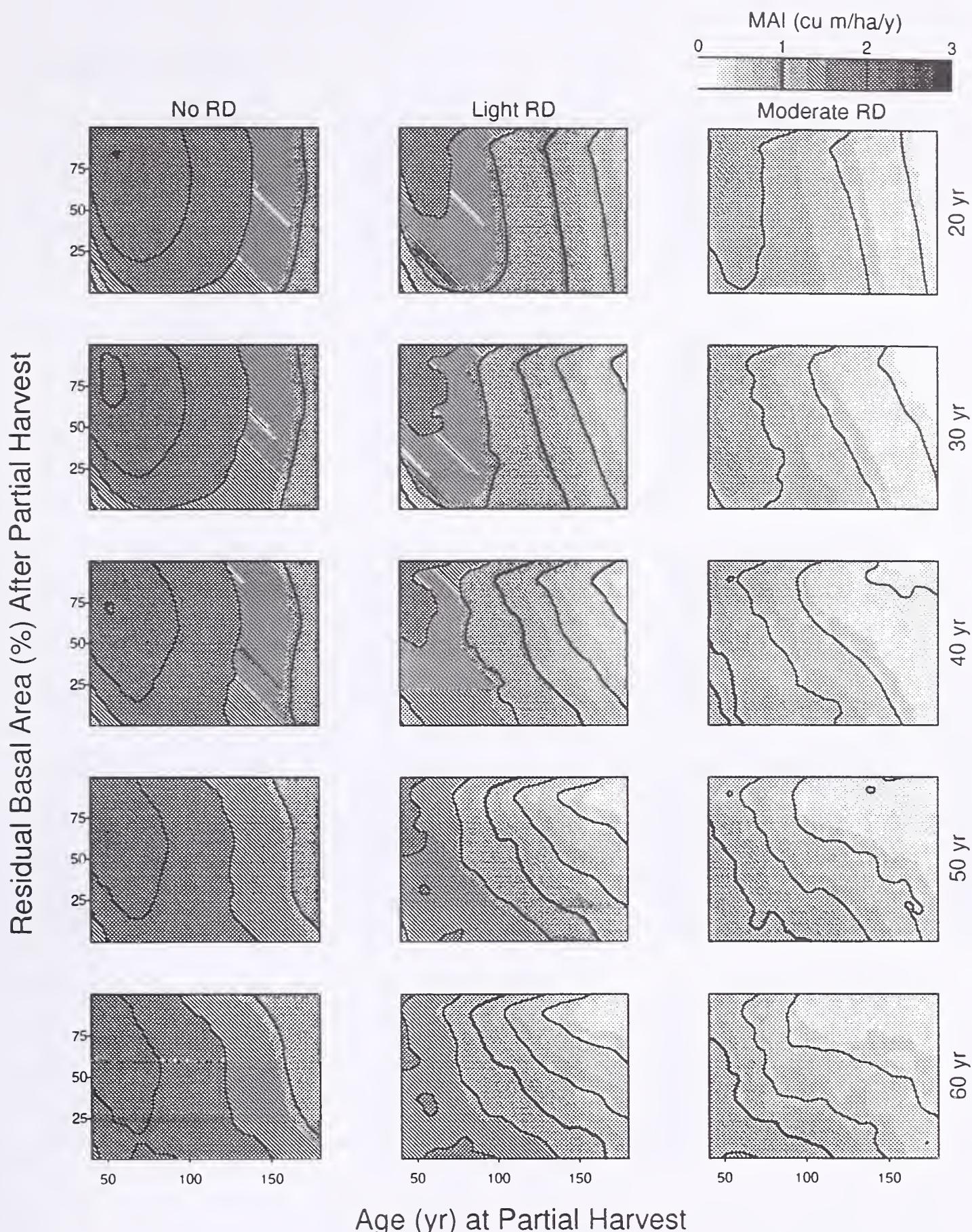
Figure 1—MAI (m³ ha⁻¹ yr⁻¹) changes in response to variation in four factors for the FdLw timber type in the IDFdm2 subzone. The response surfaces summarize the results of 2,475 simulation runs with differences in root disease level (columns), time between first and second entry (rows), age at first entry (horizontal axis) and residual basal area (vertical axis). Contour lines in these plots connect combinations of residual basal area and entry age having the same first rotation MAI. Thick contour lines show integer levels of equal MAI, with thinner contour lines marking the 0.25, 0.50, and 0.75 levels between each integer value, as shown in the gray scale legend.
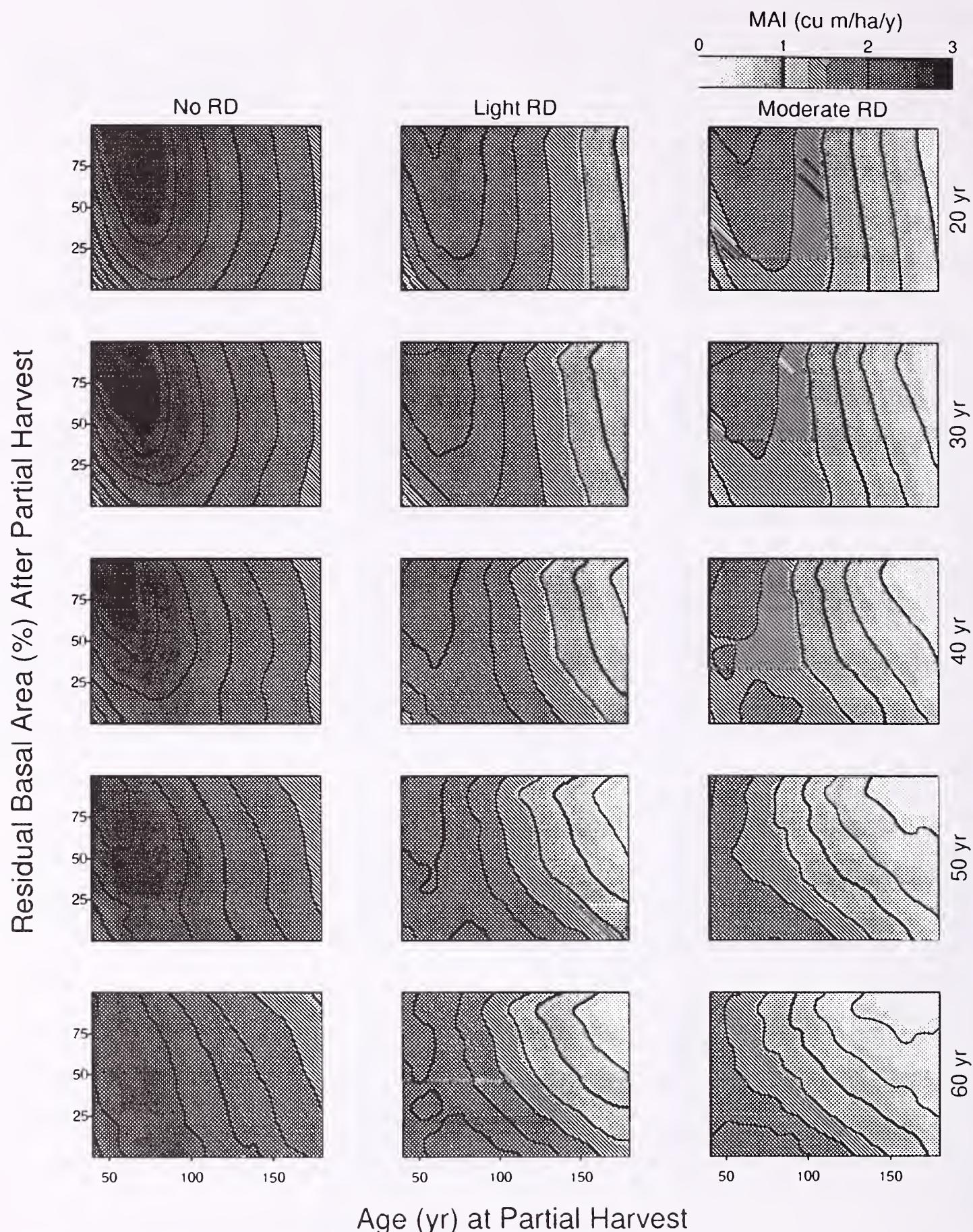
Figure 2—MAI ($m^3 ha^{-1} yr^{-1}$) changes in response to variation in four factors for the PlFd timber type in the MSdm1 subzone.

Table 3—Characteristics of partial harvesting strategies that deliver the best MAI averaged over two rotations, for FdLw stands in the IDFdm2 BEC subzone, with three levels of root disease prevalence and various Forest Practice Code harvest constraints.

RD level	Partial harvest management restriction		Age at first entry (yr)	Residual basal area (RBA percent)	Final entry (yr after first entry)	MAI over two rotations (m³ ha⁻¹ yr⁻¹)
None	Overall		50-70	50-90	30-60	1.47 - 1.49
	70 percent RBA		50-80	70	30-50	1.44 - 1.49
	40 percent RBA		60-80	40	40-60	1.40 - 1.45
Light	Overall		60-100	0-10	50-60	1.26 - 1.35
	70 percent RBA	A	40-50	70	30-50	1.19 - 1.26
		B	60-70	70	20-40	
	40 percent RBA		40-70	40	40-60	1.17 - 1.23
Moderate	Overall	A	70-100	0	*n/a*	1.05 - 1.16
		B	50-80	10	60	
		C	50	40	60	
	70 percent RBA		40-60	70	20-60	0.86 - 0.99
	40 percent RBA		50-70	40	40-60	0.92 - 1.06

Conclusions

This analysis used the Prognosis model with the Western Root Disease extension to explore the impacts of alternative partial cutting regimes and different levels of Armillaria root disease on mean annual increment in 24 different combinations of BEC subzones and timber types. As expected, yield projections are reduced in the presence of root disease, but impacts are also sensitive to stand species composition, timing of stand entries, level of basal area removal and regeneration. The presence of root disease alters the management strategy that is likely to obtain the highest yield.

The increasing use of partial harvesting heightens the need for further validation and calibration of those simulation models that can assess the consequences of this management action. Model calibration requires data specifically obtained from experiments that establish and monitor permanent sample plots in stands with varying levels of root disease and subjected to partial cutting. The experience of Adaptive Management (Holling 1978; Walters 1986) has shown that models play an important role in developing an understanding of ecosystem behavior. In the present context, careful experimental design, implementation, and monitoring will increase our understanding of the linkages between the proposed actions and the resulting changes in such indicators as timber yield, stand structure, and stand composition. Moreover, models also support the statistical design of experiments by identifying in advance, the possible range and variability of expected outcomes of treatments, and by identifying major uncertainties. The practice of partial cutting should be accompanied by operational experiments of this kind, coupled with monitoring programs whose results will provide feedback to model developers and decisionmakers.

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Sensitivity Analysis of Insect and Disease Model Extensions

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Abstract—Most FVS insect and disease model extensions are a blend of process modeling and empirical relationships. Because of the process elements, insect and disease models can present unexpected results when simulated conditions are unlike those tested when the model was developed. Sensitivity analysis is a systematic procedure to test the model reaction to changes in inputs. It can expose a range of model problems, as well as indicate the level of precision the model can provide for changes in inputs. Statistical procedures have been employed for sensitivity analysis for FVS insect and disease models, including the annosus root disease model, western root disease model, and the dwarf mistletoe model. Graphical procedures have been used for the sensitivity analysis of the Westwide Pine Beetle Model and some aspects of the annosus root disease model. These analyses have produced useful information concerning both the construction and the operation of the models.

Over the last several years, the Forest Health Technology Enterprise Team, and its predecessor, the Methods Applications Group, have organized and implemented a set of insect and disease impact models as Forest Vegetation Simulator (FVS) extensions. As part of the model development process, a program of sensitivity testing has been employed to explore these models' behaviors. Sensitivity analysis can be defined as the systematic testing of model input changes to produce changes in outputs. Complex models require this kind of analysis because the interactions of the model components cannot be practically predicted by mathematical analyses.

Sensitivity analysis is valuable early in the testing process to find errors in the model, since it includes running the model with many combinations of inputs. Later in the testing phase, sensitivity analysis will show how much an output will change given a fixed change in an input. This is the original conception of sensitivity analysis, that is: how sensitive is the output given a change in the input? These results can be examined with the goal of improving the model to better match experts' assessments of reality. Finally, the sensitivity results of the completed model can guide the user in performing meaningful analyses. For example, the number of alternatives modeled should correspond to the sensitivity of the model within the range to be tested. Where the outputs vary little within the range of interest, few alternatives are needed; large variability requires more alternatives.

Significant differences exist between the bases of the base FVS model and the insect and disease extensions. FVS models are based on statistical growth formulae and limiting functions using principles such as stand density index. The insect and disease models are more process-model based, lacking the inherent predictability of statistical models. Also, many of them use stochastic processes modeled with random variates. This modeling procedure adds to the need for sensitivity testing and also to that testing's difficulties.

The biggest challenge in performing sensitivity analyses for models such as the insect and disease extensions is the large number of inputs and outputs. Each stand and management scenario represents a unique set of inputs. Outputs can be represented by stands or stand summaries at a large number of points in time. Also, the use of random variates requires additional runs to produce accurate means and to give a sense of variation in outputs.

Testing Methodologies

Marsden published the first sensitivity tests of an FVS insect and disease model, the Western Root Disease Model. In one publication (Marsden, 1992a), he made graphical presentations to demonstrate the sensitivity of the model to the number, size, and locations of root disease centers. He also linked this information to the forest inventory system, showing how lack of inventory information about root disease would effect model precision. In Marsden, 1992b, he explored the model results with changes in the amount of root disease present, using the following variables:

- Number of root disease centers
- Proportion of trees infected
- Proportion of the root system colonized
- Area infected

Two random number seeds were used as treatment levels for a variable included to determine the effect of the stochastic variation in the model. Four stands were used as replicates.

The analysis used a statistical approach, with a standard experimental design and results displayed in analysis of variance (ANOVA) tables. This required 132 FVS runs. Analyses were done for both *armillaria* and *phellinus*. Using this statistical approach has strengths and weaknesses. On the positive side, it is a systematic way of testing several variables at once, and it uses a well understood analytical approach. On the negative side, a separate

ANOVA is required for each FVS cycle and each output variable, creating a large amount of data and making interpretation of results difficult. Also, a large number of runs are necessary.

Marsden (1992b) examined the amount of inventory information available in relation to the random assignment of disease centers in the Western Root Disease Model. He found timber inventory procedures may not give information with enough precision to provide the model with needed inputs. He also demonstrated how variation could be introduced into model results due to random assignment of disease centers.

Chen and others (1993) performed an ANOVA procedure on the Interim Dwarf Mistletoe Model. They tested three user parameters (MISTMULT, MISTGMOD, MISTMORT) at three levels, with runs for five stands each of Douglas-fir and lodgepole pine. Five output variables were examined. Information presented is useful to guide users in making adjustment to the parameters.

Jares and Chen (1991) used the ANOVA approach with the draft Annosus Root Disease Model with some notable differences. In Marsden (1992b) and Chen and others (1993), a complete design was used, meaning that each level of each input variables was contained in a run with each level of all the other variables. This was practical for tests using four or five variables, with stochastic replicates being one of the variables. The Jares and Chen analysis was designed as a method of screening of variables, to make a general assessment of the relative importance of the major input variables. To accomplish this, eight input variables were chosen for testing. Also, since preliminary testing had shown that the results were highly sensitive to the stochastic effect of the model's random variates, the runs were replicated with 10 random number seeds. Because of the large number of combinations of variables required for a complete design, a fractional factorial design was used. This means that not all combinations were used. The statistical "cost" of this partial design is that the significance of interaction terms can not be fully determined in the ANOVA. This confounding was not seen as a problem since this was a screening exercise.

After the Annosus Root Disease Model was completed, the model was reanalyzed (Zhang and others 1997). The results were analyzed for eight input factors and nine output variables, tested for two sets of input levels ("small" and "large" changes), and examined at years 50 and 100 of the projection.

Additional analyses were performed, focused particularly on the effects of the random variates. The Combined Root Disease Model has 27 random variates, not all of which are used in every run. This fact has significant effects on the model's sensitivity, since output can vary significantly with different seeds. One of the analyses performed demonstrates this effect. The model was run 120 times using the same FVS simulation, with only the random seed changed. The stand volume projection after 50 years ranged from about 5,100 to 6,300 cubic feet (fig. 1). From these results, we can estimate that for this simulation, 20 replications would produce mean results that would be about plus or minus 4 percent of the "true" average. The "true" average in this case
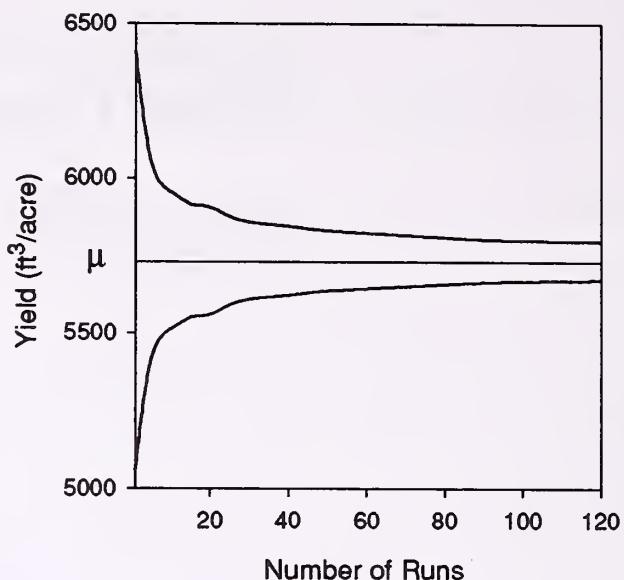

Figure 1—Expected mean yield estimate of simulations, with + and – two standard deviation bounds, for sample stand data.

is the average obtained if the model were run a very large number of times. Changing some keywords can change the random variates throughout the model, so some variation can exist even when using the same seed, but different keywords.

A comparison of the relative variation between output variables and over time is shown in figure 2 for a sample stand. The Y-axis shows the coefficient of variation in percents for the replications using different random number
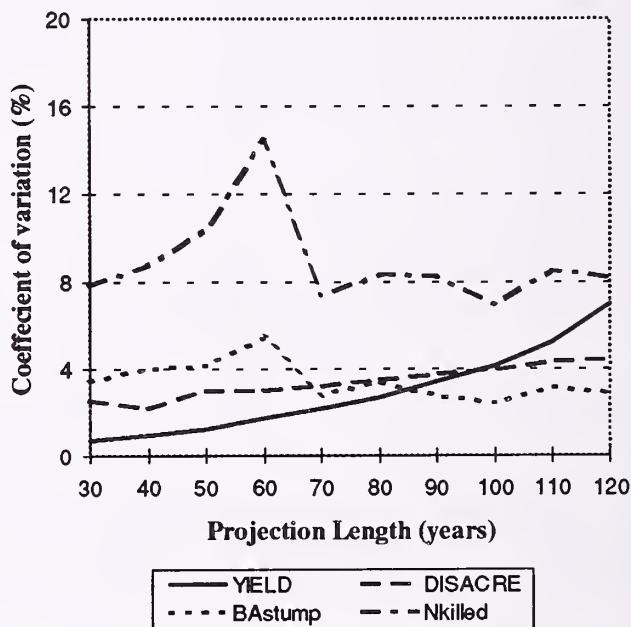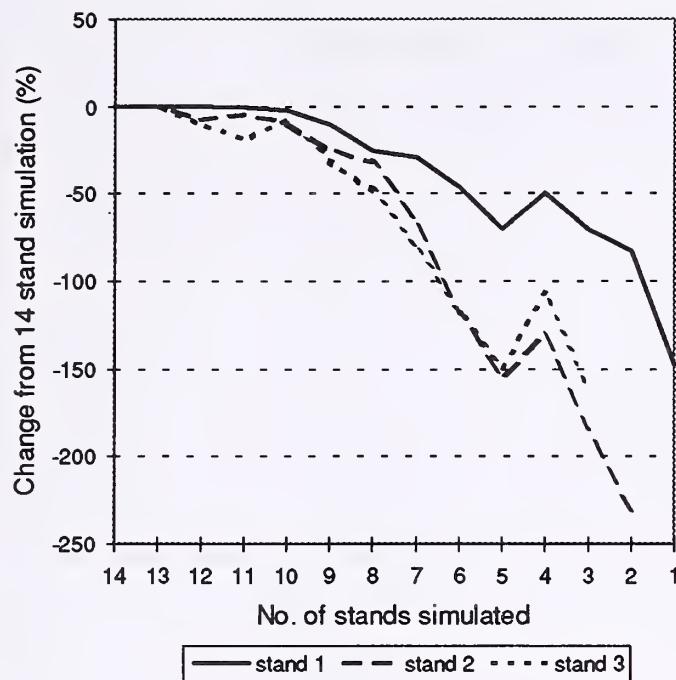

Figure 2—Coefficient of variation of replicated simulations of a single stand for four dependent variables over time.

Figure 3—Percentage change in simulated bark beetle mortality for three stands when the size of the simulated area is decreased.

seeds. Coefficient of variation is the variance divided by the mean. Each stand will have a somewhat different profile. From this figure, one can see that there will be a different number of runs to produce a given level of precision for each output variable.

Sensitivity Analysis of a Multistand Model

We have a multispecies pine beetle model under development that creates new challenges for sensitivity testing. The Westwide Pine Beetle Model (WWPB) is designed to consider bark beetle dynamics on a scale relevant to the beetles. Because they easily move between stands while in flight, areas larger than a single stand need to be considered. As with landscape analyses of all kinds, the spatial arrangement of the stands can be important, which complicated the sensitivity analysis.

A primary issue for this application is how stable are the simulation results when the area of analysis is changed: for example, will the results of two adjacent 500 acre areas simulated separately be approximately the same as all 1,000 acres simulated together? In order to test this effect with the WWPB model, we ran a set of 14 stands, then subtracted one outside stand at a time and plotted the results. Figure 3 shows results using the volume killed by beetles output variable. The consistent trend in these results suggests that

there is a structural cause for this behavior, though we have not yet explored this phenomena further.

Discussion and Conclusions _____

The insect and disease extensions' sensitivity analyses that have been published will provide the model user insight into basic change-in-input to change-in-output relationships. However the variation between FVS variants and the specific stand and management alternatives being tested may yield quite different results. Before undertaking significant projects involving FVS vegetation and insect and disease modeling, the user would be well advised to make a systematic series of runs to gain an understanding of the models' sensitivities across the range of conditions in the project. The ANOVA approach is difficult to implement and interpret, and would not be worthwhile for general users.

Part of user testing should include a simple analysis of the variation in the models due to the stochastic variables. Hamilton (1991) demonstrated that the Inland Empire Variant ran without using the insect and disease extensions can have large variation due to the random variates. He recommended that "at least two or three" runs be made using different random number seeds. We believe that the results from our analyses as displayed in figure 1 indicate this may be an even bigger issue when using the insect and disease models, and require more like 10 to 20 runs in cases such as the one shown. This variation is not a fault that model developers can fix. It generally represents a combination of a lack of detailed biological information and random processes in nature which are inherently unpredictable.

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A Comparison of Forest Vegetation Structural Stage Classifications

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Abstract—Recently, there have been considerable efforts to develop classification systems that quantify forest structure. These classification schemes define a set of forest structure categories and attempt to classify forest stands into structural stages based on physical stand characteristics. In this paper, Forest Vegetation Simulator (FVS) was used to compare and contrast four different forest structure classification systems currently in use in the Pacific Northwest. Tree-lists from FVS were used to classify example stands, under each classification system, for several simulated time periods. The resulting classifications demonstrated significant differences in structural stages between classification systems for a single point in time as well as differences in their ability to track stand development over time. From the results of the comparison, recommendations were then identified to guide the development of a refined forest structure classification system.

Today there are many different classification systems and approaches for characterizing and quantifying vertical forest structure. Most of the existing classification schemes define a set of forest structure classes and attempt to classify forest stands into various categories or structural stages based on physical stand characteristics. As one might expect, there is considerable variation in both category definitions and the rules used to classify stands into the various categories. As a growth model that provides quantitative stand characteristics both present and into the future, the Forest Vegetation Simulator (FVS) growth model (Stage 1973; Teck and others 1996; Wycoff and others 1982) represents an ideal environment for comparing and contrasting different forest structure classification systems.

Since its inception and development, FVS has been primarily used in a forest management paradigm. FVS has been used extensively to model stand development, quantify current stand conditions, predict future patterns of stand growth, and to evaluate alternative management practices and disturbances. More recently there has been the emergence of a new paradigm—the ecosystem management paradigm. The ecosystem management paradigm has promoted an increased interest in and development of FVS post processing tools to meet the challenges of new resource management objectives associated with ecosystem management. While many of these objectives are social and economic in nature, the main thrust or focus of most of these efforts is in meeting ecological objectives. Resource managers are not only charged with modeling stand development, quantifying stand conditions, and predicting growth, they are now responsible for describing or characterizing ecosystem processes such as habitat suitability and quality, forest succession, and vertical forest structure. FVS is one of the tools that managers are relying on to quantify these processes both today and in the future. With FVS and its links to visual tools like the Stand Visualization System (McGaughey 1997) and the Landscape Management System (McCarter 1995), resource managers are beginning to meet these challenges by quantitatively characterizing as well as visualizing some of these ecological processes.

One of the most significant ecological processes that has received attention over the past few years is the sequential development of forest stands. A simple illustration that demonstrates this ecological process can be conceived from our own education and experience of what the natural progression of stand development would be after a stand is harvested. For example, following a clear cut harvest, the natural progression in the absence of other disturbance would be: seedlings, saplings, poles, small saw timber, large saw timber, and old forest or old growth. While this process seems very intuitive and makes logical sense, the question that must be answered in trying to describe this process is, "How can this sequential stand development be systematically and quantitatively characterized both at a single point in time and space and over time?"

In 1994, Boise Cascade Corporation initiated the Idaho Ecosystem Management project to formulate an ecosystem management strategy for the 5.8 million acre Idaho Southern Batholith landscape in west-central Idaho. The characterization of vertical forest structure and its development over time is one of the research questions that the Idaho Ecosystem Management project staff and project partners in west-central Idaho have been faced with. In a collaborative effort to demonstrate ecosystem management, resource scientists and specialists from the Boise Cascade Corporation, the Boise, Payette, and Sawtooth National Forests, Intermountain Research, the Idaho Department of Lands, the Idaho Fish and Game, the University of Idaho, the Nature Conservancy, the Rocky Mountain Elk Foundation, and others are working together to develop a process for ecosystem management. One of the critical steps that has been

identified by project partners in implementing this ecosystem management process is the development of an ecological land classification system that is compatible for all land owners. It has further been identified that one of the primary components of this ecological land classification system is the characterization of vertical forest structure for biodiversity assessments. The system needs to be able to characterize and quantify existing vertical forest structure and systematically project vertical forest structure and stand development over time. In this way, resource managers will be able to quantify and visualize not only the existing vertical forest structure, but will have the capability to predict forest structure into the future.

With these criteria, the project staff set out to examine existing forest structure classification systems. The purpose for this comparison study then was to compare and contrast existing forest structure classification systems in the Pacific Northwest to determine which system might best meet the objectives established for the ecological land classification system in west-central Idaho.

Methodology

Four existing forest structure classification systems were selected to assess their ability to characterize vertical forest structure, to track stand development, and to understand how well they correlated with each other. In other words, how does each of the four systems represent selected forest stands and how predictable are each of the systems in tracking the sequential development of those stands. The four classifications schemes evaluated were:

- U.S. Forest Service Successional Stages (Inter-Columbia River Basin Assessment—ICRB)
- Boise Cascade Structural Stages (VEGS)
- Boise Cascade Vegetation Growth Stages (Ecological Land Units—ELU)
- U.S. Forest Service Boise National Forest Vegetative Structural Stage Model (BOISEVSS)

To compare and contrast each of the four classification schemes, five stands were selected at random from the stands inventories in Boise Cascade's Idaho Ecosystem project. Each stand was represented by sample data collected on a one-fifth acre fixed radius overstory plot and a one-fiftieth acre nested fixed radius regeneration plot.

It was determined that these five stands should be simulated through time to evaluate how well the various classification schemes tracked stand development. This was considered to be a more robust test than static point in time evaluations of the classification schemes. Boise Cascade's proprietary version of the Central Idaho FVS Model (Boise Cascade Corporation 1994, 1997) was chosen to accomplish the stand projections.

A FORTRAN routine was written to create FVS tree list and keyword files for each of the five sample stands. Each sample stand was then simulated for 50 years: five growth cycles of ten years each. Existing FVS post processors for the VEGS and BOISEVSS classification systems were used and intermediate processing algorithms were constructed to implement the ICRB and ELU systems throughout the simulation. FVS was used to project future tree lists and

selected vegetation characteristics for each projected time period for each stand. At the end of each period, FVS tree lists and selected vegetation output was then used to compute and assign a forest structure classification for each of the four classification systems.

A FORTRAN routine was written to reformat the FVS output tree list files into a format expected by the Stand Visualization System (McGaughey 1997). Color stand diagrams were produced using the Stand Visualization System (SVS) for each stand and time period, and the summary statistics for each of the classification systems were extracted from FVS output reports and assembled into tables.

Each of the forest structure classification schemes used different vegetative parameters and a different set of classification codes to describe a stand. In the following pages an overview of each approach is briefly described, and an example of the projected results of one of the randomly selected stands is illustrated and discussed.

Four Forest Structure Classification Systems

U.S. Forest Service Successional Stages (ICRB)

The ICRB successional stage classification system (O'Hara and others 1996) classifies a stand into a structural stage by quantifying the percent canopy in a preset diameter class. It uses decision tree logic that classifies a stand into a structural stage after a tree list passes a set of decision criteria of percent canopy by diameter size class. Its important to note that this classification system is limited to characterizing the stand with one variable, percent canopy, and it relies on preset diameter classes where a preset diameter class represents a range of diameters (for example, small tree class has a diameter range of 5 to 12 inch d.b.h.).

Boise Cascade Structural Stages (VEGS)

The VEGS classification system (Boise Cascade Corporation 1995) also relies on preset diameter classes; however, they are different than the preset diameter classes of the ICRB system. In addition, the VEGS system uses presence/absence logic and tests for two variables—trees per acre and basal area. For a preset diameter class to be present, it must comprise either 10 percent of total stand trees per acre or basal area. This system doesn't indicate the dominant size class in the stand, rather it groups all of the represented size classes (such as, those that meet the 10 percent requirement) into a structural stage with an additional set of size class grouping logic.

Boise Cascade Vegetation Growth Stages (ELU)

Similar to the ICRB and VEGS systems, the ELU classification system (Boise Cascade Corporation 1995) also used a different set of predefined diameter classes. Its first step is to assign a dominant size class by identifying the size class

with the maximum basal area. Next, it uses combinations of board foot volume, basal area, and trees per acre values in a stepwise approach that has built in decision logic that looks at each of these three stand characteristics simultaneously. These stand characteristic values were evaluated through a set of increasingly complex steps to make a final structural stage classification.

U.S. Forest Service, Boise National Forest Vegetative Structural Stages (BOISEVSS)

The BOISEVSS classification system in Teck (1995) first characterized a stand into a forest cover type by looking for the tree species with the maximum basal area or trees per acre. Next, it establishes a different set of preset diameter size classes that are defined differently for each possible cover type. It then determines the dominant size class by identifying the diameter size class with the maximum basal area. Once these calculations are made, it computes canopy closure and an overall description of the vertical structure (for example, single story or multi-story) using stand density index values. This system also used a stepwise approach while looking at multiple stand characteristics simultaneously and was by far the most rigorous classification system examined in terms of testing multiple variables.

Results

In general, the results of comparing and contrasting each of the four forest structure classification systems for their ability to characterize vertical forest structure and track stand development can be summarized into four overall conclusions. First, each of the systems used broad preset diameter size classes that masked out important stand structure information. Second, some of the systems dependence on presence/absence logic tended to place more emphasis on some stand structure components and less emphasis on others. Third, each of the four systems demonstrated

different inconsistencies in their ability to describe overall stand structure for any given point in time. And lastly, all four systems had difficulty in systematically tracking stand development over the 50 year period.

Table 1 illustrates the forest structure classification results for each of the four systems by projecting a single forest stand over five 10 year periods. From this table it is important to identify how each of the four systems performed. The ICRB system classified the same stand over the 50 year period into a single structural stage. The VEGS and ELU systems performed very similarly and seemed to track a change in stand develop between years 2015 and 2025. And finally, the BOISEVSS system didn't demonstrate a change in stand development until year 2035, and it tended to inconsistently characterize single story and multi-story structure from year to year.

Some of the other observations that were made in the comparison study were identified by testing each of these systems with extreme cases. The two stands in table 2 represent two of the extreme cases we tested. In both extremes each of the classification systems demonstrated disproportionate variation in the resulting structural stage classification.

An additional observation that was made in the comparison study was the potential misclassification that might occur if the classification system used presence/absence logic. For example, in figure 1 the same two stands from table 2 are depicted. In this case, using presence/absence logic, both stands could be described as having a sapling component and an old-growth component. In essence, both stands could be described as the same structural stage even though they are extremely different stands and may represent very different ecological processes.

A final observation that was made in the study was the inconsistencies that occurred in identifying overall stand structure when information was masked or lost by imposing preset diameter size classes on the stand data. In figure 2 the first graph depicts the number of trees per acre in 1 inch diameter intervals. The second graph depicts the same

Table 1—Vegetation classifications for one of the five randomly selected forest stands.

|	Year	ICRB stages	Boise Cascade VEGS	Boise Cascade ELU	BNF BOISEVSS
	1995	Stem exclusion Open canopy	Saw-medium Low density	Medium tree Low density	Mid-age forest Open canopy Multi-story
	2005	Stem exclusion Open canopy	Saw-medium Low density	Medium tree Low density	Mid-age forest Open canopy Single story
	2015	Stem exclusion Open canopy	Saw-medium Low density	Medium tree Low density	Mid-age forest Open canopy Single story
	2025	Stem exclusion Open canopy	Saw-mix Medium density	Large tree Medium density	Mid-age forest Open canopy Multi-story
	2035	Stem exclusion Open canopy	Saw-mix Medium density	Large tree Medium density	Mature forest Open canopy Single story
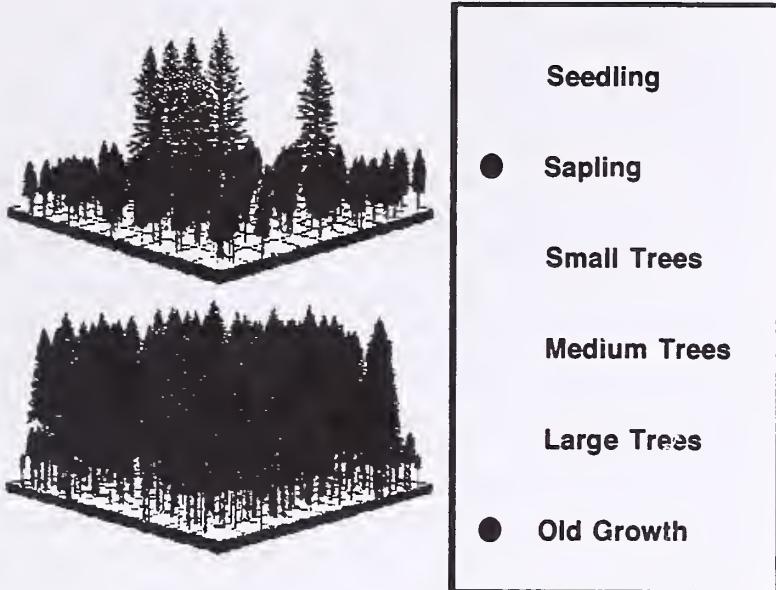
Figure 1—Failure of presence/absence logic to differentiate vastly different forest structures.

Figure 2—Examples of masked information with preset diameter classes from the forest stand.

stand data, only in this graph you can begin to see the potential information that is masked or lost when arbitrary predetermined diameter size class breaks are established. For example, based on the graph describing the stand with 1 inch diameter classes, there is a definite understory component and an obvious overstory component. In fact, this graph would most likely lead you to believe that it's a two-storied stand. In contrast, by examining the graph with preset diameter classes (for example, 0 to 2 inch, 2 to 4 inch, and so forth), it's not as conceivable that you would come to the same conclusion since much of the information on the diameter distribution is masked or hidden by preset diameter classes.

Based on the initial results of the 50 year FVS projections and the resulting classification outcomes of the four different classification systems, we made the following conclusions. First, we believe the general approach of assigning stands to various structural stage categories based on physical stand characteristics is valid. We also believe that such an approach can result in meaningful assignments once the algorithms are sufficiently refined. However, the rules for assigning stands to the various classification categories are
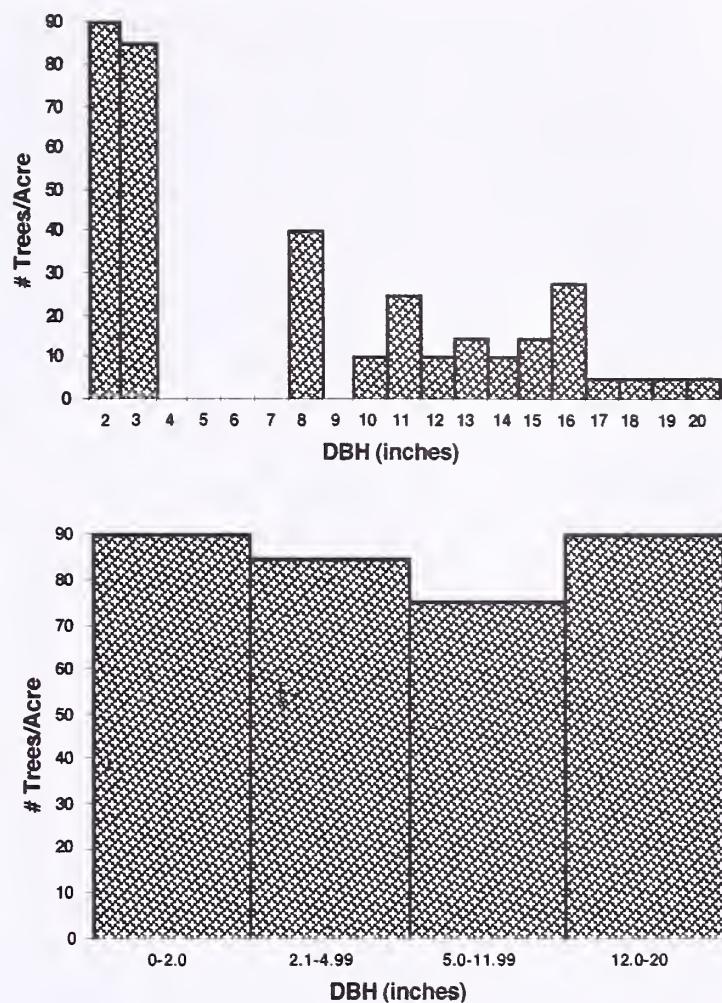
not always intuitively obvious. In light of this difficult challenge, we make the following specific recommendations for any vertical forest structure classification system:

- The classification system must first place more emphasis on overall stand structure by some prior determination, so that subsequent stand classification tests can be more accurately applied.
- The system must rely more on classification logic that addresses several stand characteristics simultaneously rather than focusing on a single stand attribute at a time.

Table 2—Structural stage classifications for two extremely different forest structures.

ICRB stages	Boise Cascade VEGS	Boise Cascade ELU	BNF BOISEVSS
Stand initiation	Saw-medium Low-density	Sapling	Grass/forb Shrub
Young forest Multi-story	Saw-medium Low density	Medium tree Stem exclusion	Mid-age forest Open canopy Single story

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- The system needs to avoid the use of rigid preset diameter size classes in defining stand size class components.
- The system should avoid exclusive reliance on presence/absence tests for diameter size class components.
- The system should refine methods to delineate between stands with a past fire history or other disturbance regimes that are important to your analysis question (for example, species composition rule bases).
- The system should use a method for computing percent canopy cover using a simple 0 to 100 percent measure that represents the percent ground area that is covered by the forest canopy.

Refined Forest Structure Classification System

Based on the results and recommendations of the comparison study, the Idaho Ecosystem Management project staff along with the guidance of project partners set out to construct a refined vertical forest structure classification system. Four specific guidelines were used to develop the revised system.

The first guideline was to use a stepwise approach that places more emphasis on overall stand characteristics, and less emphasis on rigid, preset classification logic and rules bases. Preset hard and fast rules, when applied without considering the overall character of the stand, have the potential to result in misclassifications. For example, by knowing beforehand that the stand fits the definition of a single-storied stand and does not fit the definition of a two-storied or multi-storied stand, more rigorous tests can then be applied to the resulting single-storied stand.

The second guideline was to discern meaningful forest structure categories from the actual stand data. In other words, analyze the tree diameter and height distribution data and discern meaningful categories from the raw stand data (such as, look for gaps or patterns in the distributions).

The third guideline was to minimize the use of predefined or preset diameter size classes, and instead, assign meaningful diameter size class definitions after the analysis of the stand data is complete. By examining the entire stand data set without preset diameter classes, you can avoid masking out information that is important for determining the overall structure and size classes of the stand.

The fourth and last guideline that was used in developing the refined forest structure classification system was to examine several stand characteristics simultaneously: stand trees per acre, basal area per acre distribution, crown closure, and so forth. Many stand characteristics are meaningless in a isolated setting. It is only when they are evaluated in the context of the whole stand that one can discern their true importance. For example, if you concentrate solely on stem counts, you give ample consideration to small regeneration class trees, but underestimate the importance of the large diameter trees. Conversely, if you concentrate solely on basal area or crown area, you give ample weight to the large diameter trees, but underestimate the importance of regeneration class trees.

With these four guidelines, a conceptual model flowchart of a logic-based classification scheme was developed as shown in figure 3. The conceptual flowchart first attempted

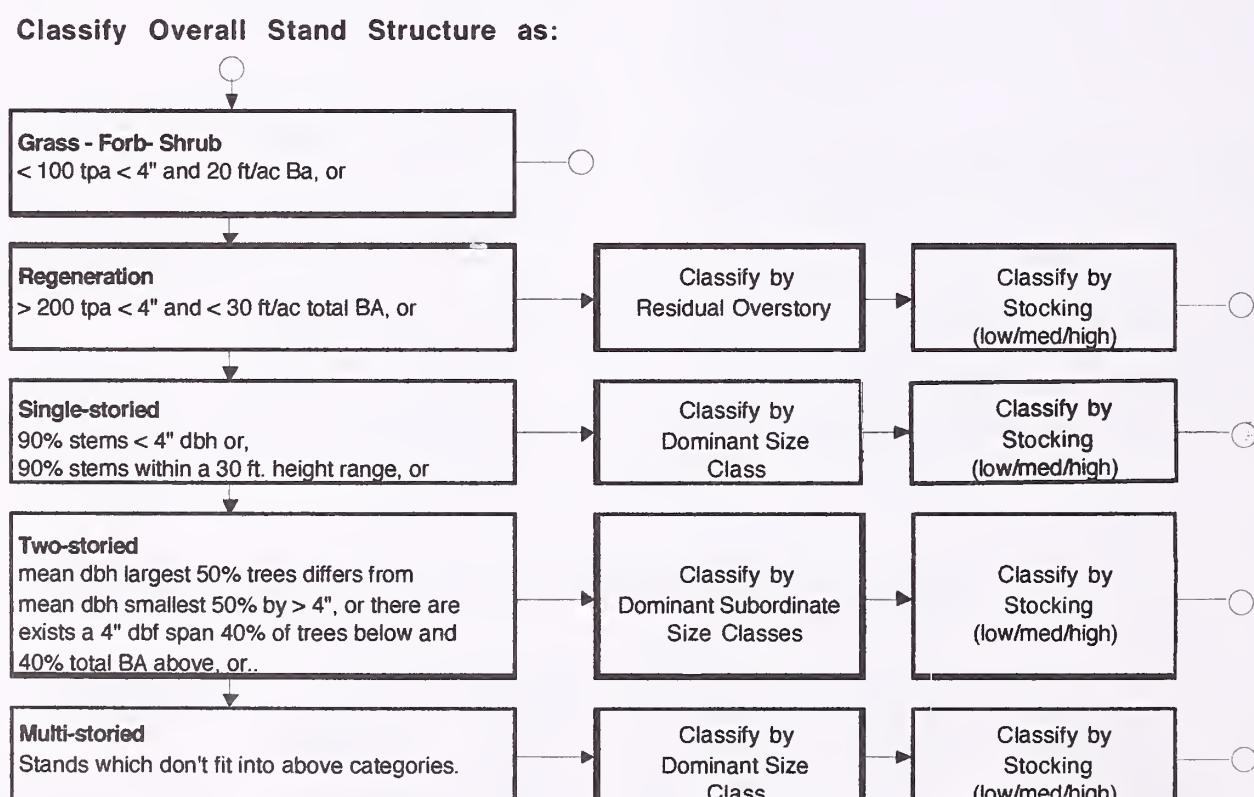**Classify Overall Stand Structure as:**

Figure 3—Logic flow for a conceptual stand classification system using overall stand structure as a primary decision criteria.

to define overall stand structure, and then it took advantage of this knowledge in subsequent classification logic and assigned a forest structure size class, a measure of stand density, an evaluation of past fire disturbance, and a final forest structural stage classification.

Revised Forest Structure Stand Classification Steps

Assign Overall Stand Structure

The first task that the refined stand classification system performed was to assign an overall stand structure for the stand. There are five possible classifications for overall stand structure: grass/forb/shrub, regeneration, single-storied, two-storied, and all-aged or multi-storied. The algorithm tests for each of these structures in a stepwise manner in the order listed. The sequential, stepwise nature of the algorithm as illustrated in figure 3 was an important key to the classification logic. The classification algorithm steps down through a sequence of increasingly complex tests, until the stand meets the requirements for a particular structural classification. At every point in the classification process, the algorithm depended on the results of previous stand tests, which have defined what the stand was *not* in order to define what the stand was. The stepwise tests for assigning each of the five overall stand structures were developed in an iterative manner by developing, evaluating, and refining the tests on a suite of selected and generated example stands.

Figure 4—The sliding window applied on a diameter distribution to determine a final size class.

Assign Size Class

Once an overall structure was assigned, a different set of classification rules were developed to determine the size class. These rules incorporated various pieces of information that were known about each stand structure to determine the size class(es) present. To avoid problems associated with rigid preset size classes discussed in the comparison study, the concept of a "sliding d.b.h. window" was developed (fig. 4). The sliding d.b.h. window was a fixed-width window that was moved across the diameter distribution 1 inch at a time.

For example, say you chose to use a 5 inch d.b.h. window, the process would be to first compute the number of trees in the 1 to 5 inch d.b.h. range, then the 2 to 6 inch range, the 3 to 7 inch range, and so forth. At the end of this process, you can accurately determine the 5 inch diameter class that contains the most trees per acre. Contrast this approach with simply computing trees per acre in the fixed size classes 1 to 5 inch, 6 to 10 inch, and so forth. If an even-aged stand has the majority of its trees straddling the 1 to 5 inch and 6 to 10 inch size class boundary, there is a good chance the stand will be misclassified as an all-aged multi-storied stand because the trees are split between the two size classes. The sliding window approach avoids these problems, and allows the stand structure to be classified from the data itself. For example, by using the sliding window illustrated in figure 4, the overall stand structure would be considered a single-storied stand since 81 percent of the trees per acre fell into one of the 5 inch moving windows describing the largest percentage of the diameter distribution. Next, additional size class rules, which were defined for each overall stand structure, would place this stand into a "Small Tree Single-story Low Density" classification because the sliding window demonstrated that the majority of trees in the stand fell between the 5 to 6 inch diameter range.

Assign Stand Density

The next step in the conceptual model classification logic was to assign a measure for canopy closure or stand density. In this classification model, stand density was measured by computing a ratio between the actual stand density index (SDI) and the maximum SDI considered possible for the stand (Teck 1995). In this algorithm the maximum SDI was assigned according to the group of dominant species in the stand. The species were grouped according to their SDI value, and the basal area for each of these groups were totaled. The maximum SDI was assigned according to the group that had the maximum basal area. The overall SDI for the stand was a total of the stand density indexes that were computed in each 1 inch diameter interval. The stand SDI was divided by the maximum SDI and converted into a percentage. If the resulting percentage was less than five, the stand was redefined as a grass/forb/shrub stand. Otherwise, the stand density was divided into three density classes: low density (5 to 30 percent), medium density (31 to 70 percent), and high density (71 to 100 percent).
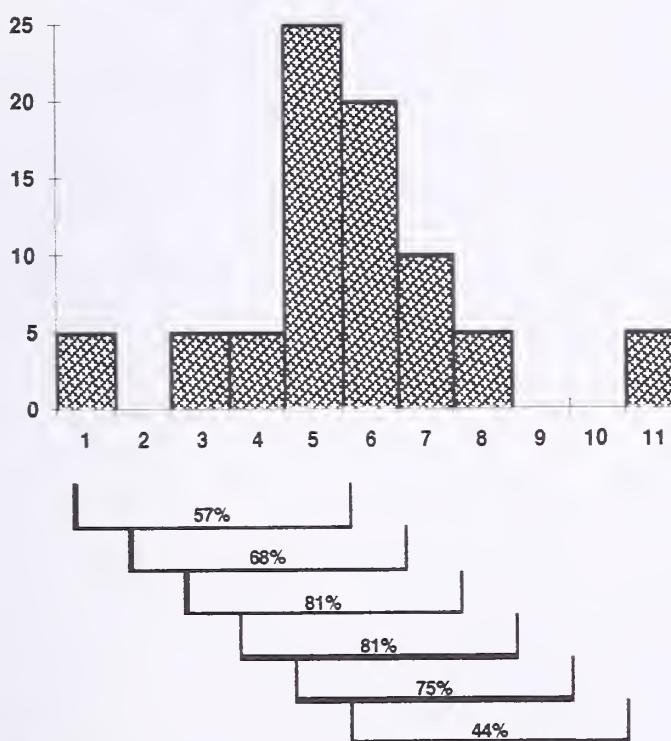
Assign Fire History

A fourth step in the structural stage classification was the assignment of a fire history classification, an important characterization for the ecological land classification system in west-central Idaho. Tree stands with a fire history would be expected to have stand structures conspicuously lacking the smaller subordinate tree classes. This lack of subordinate tree classes was assumed due to past fires that killed the smaller, fire susceptible trees. Conversely, the "without fire" stand classifications would have all tree size classes represented in the stand, indicating that the stand had not been subjected to any past fires. A final fire history code was assigned to the final forest structure based on species composition and the number of trees per acre decision logic. A specific set of rule bases have been developed for a limited number of habitat types in west-central Idaho, and have been put into the refined classification to begin to test and further develop a more refined set of rule bases for identifying forest stands with past fire histories.

Assign Final Forest Structure

Once the tree list had passed all of the above tests, a final forest structure was determined and a final forest structure classification code was assigned. These codes were then used as input into ecological land classification system and geographic information system databases. In addition, the final codes were converted into a numeric format for output by FVS into FORPLAN (Johnson and others 1986) yield tables and database files.

Conclusions

Based on the results of the comparison study and all of the concepts that were developed into the refined forest structure classification system, it is evident as it is with any classification system development that there must be continuous system validation and testing. In the Idaho Ecosystem Management Project, validation and testing of the refined system is ongoing and will continue to improve the classification system to one that is compatible for all land owners in west-central Idaho. In addition, with the challenge of developing forest structure classification systems to meet the new resource objectives associated with ecosystem management, it is imperative that all land owners continue to pursue collaborative partnerships in these classification efforts. And finally, as with all research and analytical tool development, it's important to reiterate the need to continue to explore and answer these research questions while striving for continuous improvement and excellence.

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The Forest Vegetation Simulator (FVS) is a computer program that projects the development of forest stands throughout the United States. This proceedings of the First FVS Conference held in Fort Collins, CO, includes 33 papers dealing with habitat modeling, landscape analysis, forest planning, forest health assessment, ecological processes, modeling vegetation dynamics, and new technologies.

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